ORIGINAL ARTICLE

Negative neurofunctional effects of frequency, depth and environment in recreational scuba diving: the Geneva ''memory dive'' study

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Objectives: To explore relationships between scuba diving activity, brain, and behaviour, and more specifically between global cerebral blood flow (CBF) or cognitive performance and total, annual, or last 6 months' frequencies, for standard dives or dives performed below 40 m, in cold water or warm sea geographical environments.

Methods: A prospective cohort study was used to examine divers from diving clubs around Lac Léman and Geneva University Hospital. The subjects were 215 healthy recreational divers (diving with self-contained underwater breathing apparatus). Main outcome measures were: measurement of global CBF by ^{133}Xe SPECT (single photon emission computed tomography); psychometric and neuropsychological tests to assess perceptual-motor abilities, spatial discrimination, attentional resources, executive functioning, and memory; evaluation of scuba diving activity by questionnaire focusing on number and maximum depth of dives and geographical site of the diving activity (cold water *v* warm water); and body composition analyses (BMI).

Results: (1) A negative influence of depth of dives on CBF and its combined effect with BMI and age was found. (2) A specific diving environment (more than 80% of dives in lakes) had a negative effect on CBF. (3) Depth and number of dives had a negative influence on cognitive performance (speed, flexibility and inhibition processing in attentional tasks). (4) A negative effect of a specific diving environment on cognitive performance (flexibility and inhibition components) was found.

Conclusions: Scuba diving may have long-term negative neurofunctional effects when performed in extreme conditions, namely cold water, with more than 100 dives per year, and maximal depth below 40 m.

Diving with self-contained underwater breathing apparatus (scuba diving) has become a popular sport worldwide. It is a safe sport but can become dangerous when practiced in extreme conditions (deep dives, speleological dives, and diving in extreme environments such as under ice water). The number of licensed divers has doubled within a decade while the accident rate remains very low (0.04%). Diving accidents are mostly described as acute events related to decompression or barotraumatism.

On the one hand, since the mid 1970s, several studies have underlined possible negative neurofunctional consequences of scuba diving and their relationship with neurological and cognitive deterioration after neuropsychological assessment of brain function or brain imaging. Peters *et al* found that seven out of 19 professional divers with decompression sickness (DCS) presented evidence of (1) deficient memory as determined by the Wechsler memory scale and the Supraspan test, and (2) deficient visual attention as determined by the Trail Making test.[1] Di Piero *et al* observed brain SPECT perfusion abnormalities in professional divers under hyperbaric oxygenation breathing conditions.[2] These observations have been extended to commercial divers without DCS: deep diving activity could be related to neurological symptoms.[3 4] Furthermore, excessive activity was also reported to reduced intellectual capacity. Edmonds and Boughton found that 11 professional Australian abalone divers in a group of 30 showed impairment of intellectual capacity not related to confounding factors such as alcoholism or decompression sickness history.[5] Moreover, Tetzlaff *et al* demonstrated that elderly former commercial divers without decompression sickness history are at risk of detrimental long-term effects on the central nervous system and that decreased neuropsychological performances correlated with increased prevalence of white matter lesions.[6] A significant decrease of performance in the Trail Making test form B was observed in divers, suggesting impairment of visual tracking performance.

On the other hand, the long-term neurological effects of recreational diving remain a controversial issue. If recreational divers suffer the same effects as commercial and professional divers,[7] there may be long-term risks associated with recreational diving without a history of DCS. Reul *et al* suggested that recreational diving may be harmful, as shown by the significantly higher prevalence of central nervous MRI abnormalities in divers than in controls.[8] The significance of these structural MRI abnormalities, their clinical relevance, and their etiology, as well as the size of the samples, are still much debated.[9–11] Even though interesting new studies have emphasized the role of patent foramen ovale in the pathogenesis of multiple brain lesions, no definite conclusions can yet be drawn.[12–15]

To explore the association between recreational scuba diving and neurofunctional performance, we designed a large-scale longitudinal prospective study (the ''Geneva memory dive'' study), in which we focused upon correlations between diving activity (frequency of diving, deep diving, or cold water diving), specific cognitive performance, and quantitative cerebral blood flow. To our knowledge, this is the first prospective study looking at these relationships in recreational divers. Assessing brain function by both quantitative functional imaging techniques and neuropsychological

Abbreviations: CBF, cerebral blood flow; DCS, decompression sickness; SPECT, single photon emission computed tomography specific evaluations will help clarify this issue. We hypothesize that quantitative assessment of CBF may be valuable for screening divers for potential brain dysfunction and may be optimized by evaluating the cognitive functioning of all subjects using standardized neuropsychological tests. The initial cross-sectional results (that is, for the first assessment) are presented here.

METHODS

Subjects

A total of 268 volunteers were recruited by advertisement from the recreational scuba diving community around Lac Léman (Geneva, Switzerland). All subjects were informed of the research content and the agreement of the Geneva University Hospital ethical committee and gave their written informed consent for participation. The protocol included medical history, neurological status, blood analysis (glucose, HDL, LDL, cholesterol, triglycerides), body composition analysis (BMI, DXA[16]), neuropsychological/psychometric testing, and cerebral blood flow measurement (^{133}Xe SPECT[17]). Sixteen divers were excluded because of a medical history of decompression sickness, six because of their medical history (multiple sclerosis, cerebral aneurysm, epilepsy, coronary diseases) and 31 because of uncompleted files (psychometric testing or SPECT were not performed or not analyzable). Therefore, a total of 215 healthy subjects that met the inclusion criteria listed in table 1 were retained for further analysis.

Scuba diving history and activity

Each diver was asked to fill in a detailed questionnaire carefully reviewed during medical evaluation. Each questionnaire requested a precise description of overall scuba diving activity as well as activity undertaken during the last 6 months in terms of the number of total dives and the number of dives above and below 40 m. It also requested the following information: (1) certification authority, (2) level of scuba diving training, (3) number of years of activity (NY-D), (4) number of total dives performed (DTot), (5) number of ''standard'' dives (DS), that is above 40 m, (6) number of dives below 40 m (DB40), (7) annual rate of overall dives performed (AR-DTot) calculated as DTot divided by the number of years of activity, (8) annual rate of standard dives (AR-DS) calculated as the number of ''standard'' dives divided by the number of years of activity, (9) annual rate of below 40 m dives (AR-DB40), calculated as the number of dives performed below 40 m divided by the number of years of activity, (10) number of dives during the last 6 months (DTot-6m), (11) number of ''standard'' dives during the last 6 months (DS-6m), (12) number of dives below 40 m during the last 6 months (DB40-6m) and (13) ''diving environment''. This latter parameter was defined depending on the proportion of dives performed in Lac Léman or the equivalent versus in sea water during vacation (Mediterranean, Red, or other warm seas). Scuba divers were categorized into three groups: (1) more than 80% of scuba diving activity in warm seas (WS divers), (2) intermediate activity (that is, between 20 and 80% of dives in lakes) (INT divers), and (3) more than 80% of activity in lakes (LK divers).

The accuracy of the diving activity questionnaire was assessed by Pearson's correlations between annual rate of scuba diving and activity for the last 6 months. Strong and highly significant correlations were observed between annual rate and number of total dives performed during the last 6 months ($R = 0.66$, $p<0.0001$), annual rate and number of ''standard'' dives (that is above 40 m) for the last 6 months ($R = 0.59$, $p<0.0001$), and annual rate and number of dives below 40 m for the last 6 months ($R = 0.57$, $p<0.0001$).

Table 1 Inclusion criteria used to select the healthy scuba divers

No diagnosis of depression
No psychiatric disease
No neurological disease
No current use of the following medication:
Antipsychotic
Antidepressant
Anticonvulsant
Antiparkinson
Antidiabetics
Narcotics
Methyldopa
Clonidine
Diamox
Hydergine
Cognitive enhancing medication
No blindness
No diabetes
No hypertension
No vascular disease
No artheriosclerosis
No history of decompression illness

Functional brain imaging

Inhaled ^{133}Xe SPECT was used to measure brain perfusion.[18–21] The gas ^{133}Xe was obtained from a commercial source (Dupont Pharma Xenon, Heider, Switzerland) and was administered to subjects using the dispenser system (Ceretronix XAS SM32C, Randers, Denmark). SPECT acquisition was performed using a 3-heads Toshiba GCA-9300 camera with LESHS collimation dedicated to xenon dynamic SPECT acquisition (''parallel-holes low-energy superhigh-sensitivity''). The subjects were in a decubitus position with eyes closed and ears plugged. Technical details of acquisition and reconstruction have been described previously.[18] Dedicated protocols enabled the simultaneous determination of CBF in all brain regions in a single 10-min acquisition. Regional CBF was determined using the ''Early Picture'' method of calculation, which provided a coefficient of variation of 6.3%.[22] The cerebral blood flow measure was expressed in terms of global CBF in ml/min/100 g of cerebral tissue. An illustrated case is shown in figure 1. Due to large gender differences in CBF measurement, crude global CBF (gCBF) scores were converted into gender-related T scores as previously described.[18]

Neuropsychological and psychometric testing

All subjects underwent, individually and under controlled laboratory conditions, a session of both computerized and paper and pencil tests. The test battery consisted of tests to assess perceptual-motor abilities, spatial discrimination, attentional resources, executive functioning, and memory, as suggested in the literature on professional divers.[23–27]

The Mill Hill multiple-choice vocabulary scale[28] was used as a measure of general knowledge which was assessed in terms of the number of items correctly discriminated (MHB). Formal and semantic verbal fluency tasks were used to assess both verbal ability and executive function[29]; participants had to produce as many words as possible in 2 min, either animal words (semantic) or words beginning with the letter ''M'' (formal). Scores were the number of correct words in 2 min (VFF-T and VSF-T, respectively). The Five Points test was used to assess non-verbal fluency. The score was the number of correct figures produced in 3 min (NVF-T).[30] An adaptation of the Thurstone test (BG9)[31] was used to evaluate spatial discrimination and speed of information processing. The Digit Symbol test (CODE) (from the WAIS-R battery)[32] was used to measure processing speed, but it also requires spatial discrimination and planning. The Trail Making test[33] was also used. This test requires speed, visual scanning, and ability to

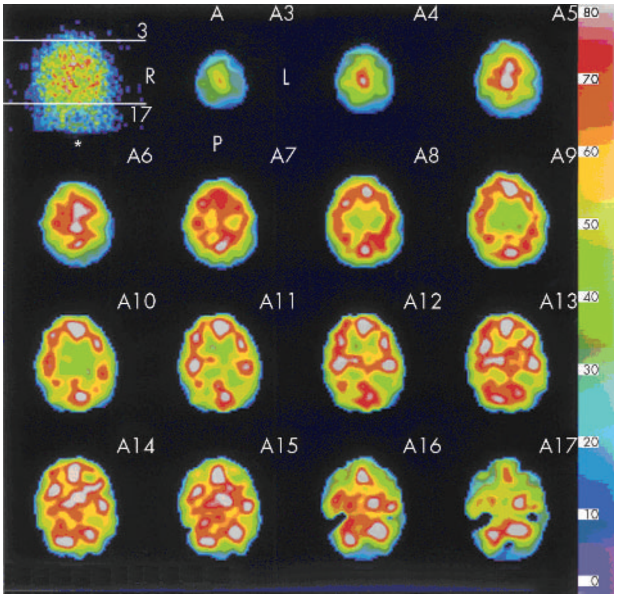

Figure 1 ^{133}Xe SPECT of a normal subject. Results are presented as successive transaxial planes from top to bottom. Brain volume is shown in 15 consecutive planes. The first plane shows planar orientation (right/left, anterior/posterior). The brain volume analysed is shown in the upper left corner. The pixel values of regional cerebral blood flow are colour-coded and expressed as a quantitative measurement in ml/min/100 g tissue.

progress in a sequence of numeric symbols in a simple task (part A) or in a more complex task (part B) alternating between letters and numeric symbols and requiring flexibility. The time required to complete each part was noted (TMT-A, TMT-B); an index of the additional processing cost entailed by part B was calculated as TMT-B minus TMT-A divided by TMT-A. Five subtests from the Test for Attentional Performance battery (TAP)[34] were selected: phasic alertness (AP), visual scanning (BVAC), flexibility (F), divided attention (AD), and working memory (MT). This test battery was chosen because of its efficacy in identifying very specific attentional deficits that go unnoticed or cannot be further discriminated with established tests. The selected subtests were the most complex of the battery and may constitute a sensitive indicator of subtle neurological impairment. The phasic alertness subtest was added in order to obtain a baseline of simple (APSS) and conditioned (APAS) reaction time. For all these tasks, performance was assessed in terms of the median (-MED), number of correct responses (-COR) and number of errors (-ER). A French adaptation of the Process-dissociation procedure using a stem-completion task (Adam and Van der Linden, personal communication) from Ste-Marie *et al*[35] was used to separate recollection from automatic influences of memory within the same task. Performance was expressed as the proportion of words correctly recalled in the inclusion (INC) or exclusion (EXC) conditions. Estimations of the relative contribution of controlled (PCC) and automatic (PCA) processing in the task were calculated from the performance in each condition (see Ste-Marie *et al*[35] for more details). For both conditions, short and long delays (respectively, 3 and 12 item intervals) were also considered. The difference in performance between inclusion and exclusion conditions reveals the degree of cognitive control.

Statistical analysis

Data analysis was conducted using STATISTICA 5.5 software (STATISTICA for Windows, StatSoft, Tulsa, USA). Diving indices, anthropometric data, CBF measurements, and cognitive performances were compared between the two extreme groups of divers (lake *v* warm sea) by Student's *t* tests for independent samples. Pearson's and partial correlations were calculated for the total cohort between diving indices and CBF or between diving indices and cognitive performances. Multiple linear regression analysis was used to further evaluate the relationship between diving indices and CBF. A stepwise procedure was used to assess their additional contribution and controlled for potential confounding (that is age and BMI). The significance of each parameter in the linear regression was calculated by Fisher's test. The stepwise procedure at each step included the parameter with the highest partial correlation if its F statistic was significant. A significance p value of less than 0.05 (two-tailed) was used for all tests.

RESULTS

Recreational scuba diving activity

Among the 215 healthy recreational scuba divers, 70 (32.6%) were women and 145 (67.4%) were men. The cohort had certification awarded by the international diving societies CMAS ($n = 74$, 34.6%), PADI ($n = 67$, 31.3%), or both societies ($n = 58$, 27.1%) or combined with other certification (SSI, NAUI; $n = 15$, 7.0%). On the basis of the new definition of competence defined by the European standardization committee CEN (European standards project for scuba divers, CEN/TC 329, http://www.cedip.org), three divers (1.4%) were CEN level 1 (supervised divers), 71 (33.2%) CEN level 2 (autonomous divers), 85 (39.7%) CEN level 3 (dive leaders) and 55 (25.7%) instructors.

When diving environment was considered, 88 (40.9%) divers performed more than 80% of their dives in cold water (Swiss lakes or neighbouring French lakes, constituting the LK group), while 32 (14.9%) divers performed at least 80% of their dives in sea water during vacation (Mediterranean, Red, or other warm seas, constituting the WS group). The altitude of the lakes could interfere with our comparison of "cold" and "warm" dives and was considered a relevant parameter per se.[36–38] Careful attention was paid to this activity. Only one subject was not included in the cohort because of diving in an extreme altitude lake (Nepali Himalayas). All subjects recruited dived in Swiss and neighbouring French lakes whose altitude was between 372 and 447 m.

The total number of dives, annual rate and number of total dives performed during the last 6 months were significantly higher for scuba divers performing most of their dives in lakes compared to warm seas (DTot: $T = 2.88$, $p = 0.005$; 441.3 ± 413.6 and 208.0 ± 224.3 dives, respectively; AR-DTot: $T = 3.27$, $p = 0.001$; 60.9 ± 39.9 and 34.8 ± 26.3 dives/year of activity; DTot-6m: $T = 4.59$, $p < 0.001$; 32.4 ± 24.9 and 8.2 ± 9.7 dives). Number of dives below 40 m (fig 2A), annual rate, and number of dives below 40 m during the last 6 months were significantly higher for the LK group compared to the WS group (DB40: $T = 3.19$, $p < 0.005$; 152.3 ± 220.3 and 20.7 ± 39.7 dives (fig 2A); AR-DB40: $T = 3.85$, $p < 0.001$; 19.0 ± 22.4 and 2.9 ± 3.3 dives/year of activity; DB40–6m: $T = 3.97$, $p < 0.001$; 10.5 ± 12.8 and 0.8 ± 1.5 dives). The number of "standard" dives during the last 6 months was also significantly higher for the LK group (DS-6m: $T = 4.13$, $p < 0.001$; 21.8 ± 18.3 and 7.1 ± 8.7 dives). Table 2 summarizes the results of the group comparisons.

Cerebral blood flow

Between-group differences

Group comparisons showed a significant reduction in gender-adjusted gCBF for LK relative to WS divers ($T = -2.25$, $p < 0.05$; -0.1 ± 1.0 and 0.4 ± 1.1) (fig 2B).

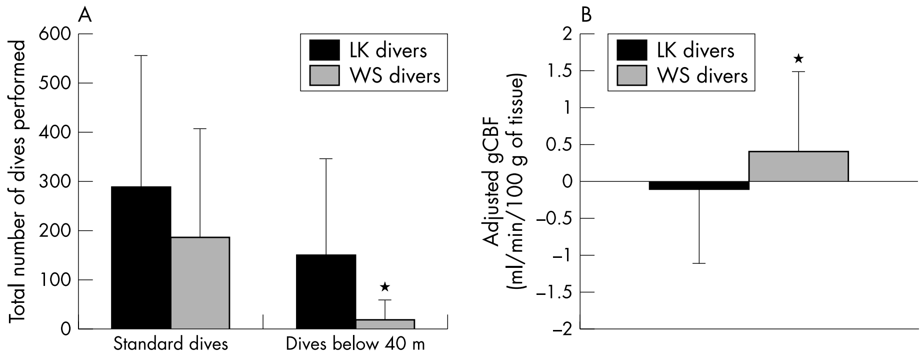

Figure 2 Between-group differences (lake *v* warm sea) in the total number of ''standard'' dives performed and dives performed below 40 m (A) and in the gender-adjusted global cerebral blood flow (gCBF) (B).

Relationship between diving indices and cerebral blood flow

Multiple stepwise linear regressions were used to evaluate the relationship between diving indices and CBF. In these analyses, step zero presents the univariate relationship (R = partial correlation) between each parameter and the tested variable. In a further step, the parameters with the highest partial correlation appear. The last step shows the independent correlations found. Table 3 summarizes the results of the multiple regressions. Gender-adjusted gCBF was significantly related to age (R = −0.48, p<0.0001), BMI (R = −0.38, p<0.0001), NY-D (R = −0.25, p<0.005), DTot (R = −0.24, p<0.01), DS (R = −0.15, p<0.05), DB40 (R = −0.28, p<0.0001), and AR-DB40 (R = −0.19, p<0.01). Only age, BMI, and DB40 were further included in the multiple regression model as independent variables to describe CBF as shown in table 3.

Cognitive performance

Between-group differences

As shown in table 4, the LK group in comparison to the WS group showed a significantly higher processing cost in the Trail Making test (TMT_AB; T = 2.48, p<0.05; 1.4±0.8 and 1.1±0.5, respectively), reduced contribution of controlled processing in the stem completion task (PCC3; T = −2.12, p<0.05; 0.67±0.19 and 0.76±19) and more words recalled in the exclusion condition (considered as errors) (EXC3; T = 2.63, p<0.05; 0.11±0.09 and 0.06±0.06).

Relationship between diving indices and cognitive performance

Partial correlations were computed between either standard dives or dives below 40 m and cognitive performances for the total cohort after partialling out the effect of age. Significant correlations were found for each of the following diving parameters:

- Total number of ''standard'' dives (DS) was negatively associated with time to complete part A of the Trail Making test (TMT-A: R = −0.17, p<0.05) and number of correct responses in the flexibility test (F_COR: R = −0.23, p = 0.001) and positively related to number of errors in the visual scanning task (BVAC_ER: R = 0.15, p<0.05). DS was associated with more words recalled in the inclusion condition of the stem completion task (INC12: R = −0.16, p<0.05; INC: R = −0.15, p<0.05) and greater contribution of automatic processing in the stem completion task (PCA12: R = 0.25, p<0.05).

Table 2 Anthropometric data, CBF measurements, and diving activity in the total cohort, in the lake divers and in the warm sea divers sub-cohorts

Diving activity	Total cohort (*n* = 215)	LK sub-cohort (*n* = 88)	WS sub-cohort (*n* = 32)	T value	Group differences, p value
Age (years)	35.7±8.1§	34.2±7.5	34.5±9.3	−0.11	0.19¶
BMI†	24.2±3.3	24.6±3.5	23.3±3.2	1.82	0.071
FM‡ (kg)	16.6±5.6	16.7±5.9	16.0±6.2	0.57	0.56
FM‡ (%)	22.3±6.0	21.9±6.1	22.7±6.9	−0.66	0.504
EDU	14.7±3.0	14.7±3.2	16.2±3.4	−2.08	0.039*
Adjusted gCBF	0.3±7	−0.1±1.0	0.4±1.1	−2.25	0.026*
NY_D (years)	6.6±5.1	7.0±5.1	6.1±7.3°	0.76	0.446
DTot	350.3±323.6	441.3±413.6	208.0±224.3	2.88	0.005**
DS	260.2±221.7	289.0±268.7	187.3±195.0	1.86	0.065
DB40	90.1±157.4	152.3±220.3	20.7±39.7	3.19	0.002**
AR-DTot	53.7±35.4	60.9±39.9	34.8±26.3	3.27	0.001**
AR-DS	41.5±26.7	41.9±26.8	31.9±24.8	1.75	0.083
AR-DB40	12.1±16.5	19.0±22.4	2.9±3.3°	3.85	<0.001***
DTot-6m	27.6±28.9	32.4±24.9	8.2±9.7	4.59	<0.001***
DS-6m	20.1±24.0	21.8±18.3	7.1±8.7	4.13	<0.001***
DB40-6m	7.3±10.4	10.5±12.8	0.8±1.5	3.97	<0.001***

†Body mass index (BMI) is defined as weight/height^2; ‡fat mass (FM) is measured by dual-energy X-ray absorptiometry (DXA); §values are means±SD; ¶Student's *t* tests; *p<0.05, **p<0.01, ***p<0.001.
Adjusted gCBF, global cerebral blood flow (adjusted for gender differences); AR, annual rate of dives from the listed parameters; DB40, total number of dives performed below 40 m; DS, total number of ''standard'' dives performed (that is above 40 m); DTot, total number of dives performed; 6m, number of dives performed during the last 6 months' dives from the listed parameters; LK, lake divers; NY-D, number of years of scuba diving; WS, warm sea divers.

Table 3 Diving indices analysis for gender-adjusted gCBF in the total cohort

Criterion	Step zero† R	Step zero† p value	Last step‡ R	Last step‡ p value
Adj gCBF				
Age	−0.48	<0.0001	−0.40	<0.0001
BMI	−0.38	<0.0001	−0.25	0.0004
NY-D (years)	−0.25	0.0005		
Dtot	−0.24	0.0006		
DS	−0.15	0.0336		
DB40	−0.28	<0.0001	−0.15	0.0148
AR-DTot	−0.11	NS		
AR-DS	−0.03	NS		
AR-DB40	−0.19	0.0076		
DTot-6m	−0.12	NS		
DS-6m	−0.10	NS		
DB40-6m	−0.11	NS		

Stepwise linear regression analysis was used. Adj gCBF = 4.10−0.521*age−0.0775*BMI−0.0010*DB40.
†Step zero shows the univariate relationship (R = partial correlation) between each parameter and the tested variable; ‡in further steps the parameter with the highest partial correlation appears. The last step shows the independent correlations found.
Adj gCBF, gCBF adjusted for gender differences; NS, non-significant correlation, $p<0.05$; R, partial correlations.

Table 4 Cognitive performance in the total cohort, and in the lake and warm sea sub-cohorts

Cognitive performance	Total cohort (*n* = 215)	LK sub-cohort (*n* = 88)	WS sub-cohort (*n* = 32)	T value	Group differences§, p value
MHB†	27.3±4.2	26.8±4.9	27.5±2.8	−0.77	0.441
VFF-T	25.4±6.8	25.7±6.5	23.9±7.3	1.20	0.232
VSF-T	38.5±8.5	37.8±8.3	38.5±6.7	−0.40	0.687
NVF-T	43.7±9.2	43.6±9.3	44.4±7.6	−0.42	0.673
BG9	28.1±5.1	27.8±5.5	29.1±4.3	−1.25	0.216
CODE	61.9±10.2	60.9±10.7	61.6±11.3	−0.28	0.780
TMTA	25.9±7.7	26.1±8.0	26.8±8.3	−0.42	0.673
TMTB	57.6±18.9	61.2±20.9	53.3±16.5	1.89	0.061
TMTA_B	1.3±0.7	1.4±0.8	1.1±0.5	2.48	0.015*
APSS_MED	231.2±27.2	228.2±24.1	226.4±25.0	0.35	0.724
APSS_COR	38.6±0.9	38.6±1.1	38.8±0.5	−1.09	0.279
APAS_MED	0.0±24.4	220.7±20.0	223.5±27.3	−0.59	0.558
APAS_COR	34.9±0.7	38.6±0.8	38.7±0.7	−0.81	0.417
BVAC_MED	2193.2±672.1	2216.1±608.5	2203.2±616.2	0.10	0.920
BVAC_COR	46.7±8.7	45.7±4.1	46.1±2.9	−0.50	0.621
BVAC_ER	3.3±3.7	3.6±4.1	3.1±2.9	0.60	0.551
F_MED	751.0±190.2	748.4±195.4	723.8±161.1	0.63	0.531
F_COR	92.3±7.2	90.9±9.8	92.9±4.9	−1.09	0.280
F_ER	2.2±2.9	2.6±3.4	2.1±2.4	0.77	0.444
AD_MED	651.5±71.4	644.8±66.4	680.2±76.3	−2.45	0.016*
AD_COR	30.6±1.8	30.5±1.8	30.3±1.7	0.58	0.566
AD_ER	0.7±1.0	0.8±1.0	0.6±0.9	0.85	0.396
MT_MED	635.0±154.5	644.9±148.1	602.2±175.8	1.30	0.195
MT_COR	13.0±1.7	13.0±1.8	13.1±1.6	−0.29	0.770
MT_OM	1.5±1.7	1.6±1.9	1.4±1.6	0.38	0.707
MT_ER	2.3±2.8	2.4±3.1	1.7±1.1	1.21	0.228
INC3	0.77	0.77±0.17	0.81±0.18	−1.16	0.248
INC12	0.76±0.16	0.74±0.16	0.79±0.14	−1.39	0.169
INC	0.80±0.16	0.78±0.12	0.82±0.11	−1.50	0.138
EXC3	0.09±0.11	0.11±0.09	0.06±0.06	2.63	0.010*
EXC12	0.14±0.09	0.12±0.10	0.14±0.08	−0.79	0.430
EXC	0.09±0.11	0.09±0.05	0.09±0.04	0.81	0.423
PCC3¶	0.69±0.05	0.67±0.19	0.76±0.19	−2.12	0.037*
PCC12	0.63±0.19	0.61±0.20	0.65±0.16	−0.82	0.414
PCC	0.70±0.19	0.69±0.14	0.74±0.12	−1.65	0.103
PCA3††	0.39±0.26	0.43±0.25	0.38±0.34	0.70	0.486
PCA12	0.46±0.22	0.43±0.20	0.47±0.23	−0.82	0.417
PCA	0.33±0.16	0.33±0.18	0.36±0.16	−0.66	0.511

†See methods section for a detailed description of the neuropsychological and psychometric tests scores; ‡values are means±SD; §Student's *t* tests; *$p<0.05$; ¶PCC3, PCC12, and PCC are calculated as inclusion−exclusion; ††PCA3, PCA12, and PCA are calculated as exclusion/(1-PCC).
LK, lake divers; WS, warm sea divers.

- Annual rate of ''standard'' dives (AR-DS) was associated with more words completed in the exclusion condition of the stem completion task (considered as errors) (EXC12: $R = 0.16$, $p<0.05$; EXC: $R = 0.17$, $p<0.05$).
- Number of ''standard'' dives for the last 6 months (DS-6m) was associated with more words completed in exclusion condition (EXC: $R = 0.16$, $p<0.05$) and reduced contribution of controlled processing in the stem completion task (PCC3: $R = -0.16$, $p<0.05$; PCC: $R = -0.16$, $p<0.05$).
- Number of dives below 40 m (DB40) was negatively associated with non-verbal fluency (NVF-T: $R = -0.22$, $p<0.001$) and positively associated with time to complete part A of the Trail Making test ($R = 0.16$, $p<0.05$).
- Annual rate of dives below 40 m (AR-DB40) was associated with fewer items correctly discriminated in the Thurstone test (BG9: $R = -0.15$, $p<0.05$) and with fewer words recalled in the exclusion condition of the stem completion task (EXC3: $R = 0.16$, $p<0.05$).

DISCUSSION

A large body of literature suggests that commercial diving related to deep diving, excessive diving, a cold water environment (hypothermia), or DCS events[1 3 5 6 23–25 39] may have long-term deleterious neurofunctional effects, while a recent study looking at non-saturation construction divers suggested that there was no evidence of such effects.[27] Because these non-saturation dives may correspond to standard recreational dives in term of diving profile, it was very important to identify whether or not recreational diving without DCS could be harmful for long-term cognitive performance.[14 40]

Both Reul *et al*[8] and Knauth *et al*[11] published results showing that diving had a deleterious effect on the structural brain. For example, Reul *et al* found that 27 out of 52 divers had a total of 86 focal MRI lesions versus 10 of the 50 control subjects showing a total of 14 lesions. Their observations remain controversial.[6 9 10 41–43] Some limitations of their studies include: (1) the method of recruitment, (2) the possibility of confounding factors related to the wide range of scuba diving activity identified, (3) controversial use of the MRI technique (intra- and inter-observer variability of reading), (4) the etiology and interpretation of ''abnormal'' hyper-intense MRI signals and particularly the unknown prevalence of MRI white matter artifacts or normal variability as a function of age,[44] (5) the statistical methods used, and (6) the limited or lack of evidence of neurofunctional consequences of structural observations (one should not treat or prevent structural change if of no clinical relevance).

Our approach aimed at exploring further the possibility of long-term neurofunctional effects of recreational scuba diving, by (1) studying a large sample, (2) using objective quantitative neurofunctional parameters (global cerebral blood flow and cognitive performance), (3) carefully evaluating diving activity in term of numbers, profiles (depth), and environment (cold water), and (4) taking into account the effects of possible confounding factors (particularly cardiovascular risk factors and body composition).

The main finding of the present study was that deep diving in cold water may have long-term neurofunctional consequences. This was supported by (1) the negative influence of dive depth on CBF and its combined effect with BMI and age, (2) the negative effect of a specific diving environment (more than 80% of dives in lakes) on CBF, (3) the negative influence of depth and number of dives on cognitive performance (speed, flexibility, and inhibition processing in attentional tasks), and (4) the negative effect of a specific diving environment on cognitive performance (flexibility and inhibition components).

To overcome sampling limitations, the study included 215 divers investigated over a period of 2 years. As demonstrated, the sampling method made it possible to study a wide range of divers, including a appropriate number of women, divers with various certification levels, very active divers as well as ''vacation'' divers, and finally, sports divers who dive deeper than 40 m as well as standard divers who always remain above the PADI threshold of 40 m. To overcome the limitations of descriptive parameters such as MRI, gCBF was measured by ^{133}Xe SPECT. This method does not rely on intermediate biological processes[45 46] and is not associated with non-flow dependant focal retention[47] as it is for the technetiated compounds ECD or HMPAO previously used for brain imaging in divers.[48] This quantitative technique is well recognized and enables identification of the normal dependant effects of age and gender differences in gCBF.[18] To overcome limited morphological observations, we combined the study of cognitive performance by means of an extensive battery of tests with quantitative measurement of CBF by means of the ^{133}Xe SPECT technique. Thus, the significant effect of diving on the flexibility and inhibition components of attention enables us to conclude that certain characteristics of diving do have repercussions not only on cerebral perfusion but also on cognitive function. These conclusions should lead to extensive analysis in a sub-cohort of ''deep divers'' in order to examine more clearly what depth limit should be recommended in recreational scuba diving. On the other hand, one must take into consideration the particular attitude towards risk assessment in this group of divers. However, this has to be proven by appropriate study to identify if the personality and character/behaviour of those diving deep and cold is different from those in the sea water/warm group.

Scuba diving involves a wide range of behaviour from recreational scuba diving 1 week a year in warm seas during vacation to very active scuba diving several time a week in a local cold lake at a depth below 40 m. The latter case could be considered an extreme sport and therefore it is not surprising that detailed analysis of the nature of scuba diving revealed selective negative effects on gCBF and psychometric measurements. Environmental factors have already been highlighted by Broome.[49] He showed that climatic and environmental conditions, particularly thermal environment, were risk factors that have to be considered in the presence of unexpected decompression sickness. Possible neuropsychological effects of deep diving have been also studied in professional divers[3 10]; Vaerners *et al* determined that one deep dive may cause an effect similar to the effect of 3.5 years of ordinary saturation diving.[25] Similarly, based on the results of a survey of occupational divers, Edmonds and Boughton suggested that excessive diving was related to intellectual deterioration.[5] Finally, cold could be linked to possible permanent brain impairment. Diving in cold water is associated with a cascade of psychological and physiological events. Anxiety responses may occur more frequently when diving in cold water with a wet suit and in an unfriendly environment and this will result in increased heart rate, respiratory rate, and air consumption.[50] Exercise in cold temperatures is also associated with respiratory heat loss[51] and inhalation of cold air induces a significant increase in diastolic pressure.[52] Overall, for an identical dive profile, diving in cold water may result in an increased nitrogen saturation state. In addition, knowing that the temperature of exhaled air is decreased, one may hypothesize that the blood wash-out of nitrogen may be lowered and therefore the increased tissue residence time of nitrogen could be associated with an increased risk of tissue alteration by local development of microbubbles, particularly in very sensitive tissue such as cerebral tissue.

Take home message

Actively practicing deep dives in cold water may result in deleterious neurofunctional effects on cerebral blood flow and cognitive performance. The depth limit that should be recommended in recreational scuba diving must be considered as well as the safety behaviour to adopt during such dives. This type of scuba diving should be considered an extreme sport which requires specific medical advice and control measures.

To our knowledge, the present study represents the first attempt to study long-term neurological effects in recreational scuba divers in a large sample of over 200 subjects by using a wide range of psychometric tests and objective quantitative parameters of global cerebral blood flow. It leads us to conclude that, apart from standard recreational diving which remains safe when performed in warm seas and at depths above 40 m, the combination of depth (below 40 m) and cold water diving appears to be associated with long-term neurological effects in active divers. Therefore this type of scuba diving should no longer be considered recreational scuba diving, but more rather an ''extreme sport'', for which specific medical advice should be considered. However, the residual risk can be lowered with increased control measures and appropriate risk assessment. A longitudinal follow-up study will be conducted to confirm these observations and warn the fast growing recreational scuba diving community against risks associated with regular deep dives in cold water.

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