Introduction

Diving is a widespread sport becoming increasingly popular with children and adolescents. In Germany, in 2017, approximately 11% of divers organized in the national sports divers' association were younger than 18 years, outside the association, the absolute numbers are considerably higher (Verband Deutscher Sporttaucher – German Underwater Federation, in reply to an inquiry of June 19, 2017). Scuba diving is of particular interest – also for this age group. So far, however, it has not been sufficiently ascertained which health effects exposure to a hyperbaric environment has in general, and how it affects an adolescent body in particular. The main focus in this context is the potential risk of decompression sickness (DCS). In the case of adults, this would seem to be associated with the occurrence of circulating venous bubbles after diving [11, 12]. The
formation of bubbles depends on the degree of nitrogen saturation, and with this, in particular on the depth of the dive, the duration of the dive, and the speed of ascent [10]. Repeated dives may increase the risk of bubbles owing to the accumulation of nitrogen [1, 3].

Also, advanced age, increased weight and body mass index (BMI), high body fat percentage and poor physical fitness influence the generation of bubbles [4–6].

A recent study suggests that there are risk factors other than those used in current algorithms to predict DCS that contribute to bubble formation and affect the individual bubble susceptibility [6].

So far, the association between bubbles and decompression risk has not yet been systematically researched with regard to children and adolescents. However, restrictions regarding depth, duration of diving, external conditions and the number of dives per day have been issued by different diving organisations as preventive measures for potential risks to young divers. These have been adapted to children and adolescents according to current decompression tables. Reliable data regarding the necessity or correctness of these guidelines do not yet exist. Lemaitre et al. [16] examined 10 young male divers using Doppler sonography after an approximately 25 min dive to an average depth of 12 m. The authors did not determine any bubble formation.

In this pilot study, we examined the occurrence of venous gas bubbles with a 2-dimensional transthoracic echocardiography after 2 standardised dives adhering to the recommended limitations. In addition, the connection with potential influencing factors such as gender, age, height, weight, BMI, body fat mass, muscle mass, physical activity and heart rate at the time of the scan was investigated.

Materials and Methods

This study was authorised by the ethics commission of the Deutsche Sporthochschule Köln, Germany and was conducted according to the standards for ethics in sport and exercise science research as well as the standards of the International Journal of Sports Medicine [15].

The research protocol, the data analysis and interpretation conform to the consensus guidelines for the use of ultrasound for diving research [20]. Discrepancies from this work were accounted for.

Participants

The current study includes 28 (15 male, 13 female) young healthy divers (Tables 1 and 2 for details). They were recruited via the internet pages of relevant companies, associations and organisations active in diving sports.

Only children with a medical certificate regarding their fitness to dive, written consent of themselves and their parents or legal guardians and without any known chronic disease were included.

Anthropometric data and medical history

Height and weight were measured, BMI was calculated. Body fat percentage and body muscle mass were determined by bioelectrical impedance analysis (BFS11 Body Composition Monitor, OMRON Medizintechnik GmbH, Mannheim, Germany). Girls and boys did not differ in that respect – with the exception of muscle mass – and are, therefore, shown together.

For 2 individuals muscle mass and body fat percentage could not be measured by the scale, which is why these data are missing.

Sociodemographic data, daily physical exercise and sports, monthly diving training, number of open water dives, type of diving licence as well as the personal medical history of the subjects were established by means of a questionnaire (modified and based on the family questionnaire of the Children's Health InterventionaL trial [14]).

Diving experience

The children had to show their diving licences and logs before participating. The age-related diving experience of the subjects was at least equivalent to the basic diving licence for children and ranged up to the advanced diving licence for adults (Table 2). Furthermore, the children regularly practised diving in a swimming pool on average 3 ± 2.3 (x ± SD) times per month and at the time of investigation had carried out an average of 23.2 ± 21.5 (x ± SD) open water dives (Table 1). None of the children reported any diving accidents or incidence of DCS prior to the study.

Dives

The subjects conducted 2 identical 25 min dives to a depth of 9–10 m on one day, standardised according to the at that time (2016) valid guidelines [23] of the Verband Deutscher Sporttaucher e.V. (VDST – German Underwater Federation) in the indoor diving centre “monte mare” in Rheinbach, Germany. The diving pool there is 10 m deep and has a water temperature of 28 °C.

One subject was excluded from a second dive after bubble analysis (see below for further details). This subject performed an additional dive on a separate day, which was not part of the statistical analysis.

Every child was accompanied by an experienced diving instructor during the dive. The accompanying buddy carried a dive computer, the children themselves did not have dive computers with them. The subjects quickly descended to the ground and remained at that depth for 20 min until the ascent. During the 20-min period at that depth the children performed various age-specific mental

| Table 1 | Anthropometric data, sporting activity and diving experience of the subjects. |
|---------|-------------------------------|-------------------------------|
|         | N   | Mean | SD  | Minimum | Maximum |
| Age [years] | 28  | 13.5 | 1.1 | 11.9     | 15.1     |
| Weight [kg]  | 28  | 55   | 11.2| 34.3     | 86       |
| Height [cm]   | 28  | 164.2| 8.2 | 145      | 180      |
| BMI [kg·m⁻²] | 28  | 20.2 | 2.8 | 15.7     | 26.5     |
| Body fat [%]  | 26  | 18.7 | 6.7 | 6        | 28       |
| Muscle mass [%] | 26  | 36.9 | 3.2 | 33       | 43       |
| Reported physical exercise and sports [min·day⁻¹] | 28  | 33.5 | 19.3| 8.6      | 85.7     |
| Open water scuba dives | 28  | 23.2 | 21.5| 0        | 100      |
| Monthly dive training in the swimming pool [month⁻¹] | 28  | 3    | 2.3 | 0        | 10       |
tasks and games conducted with moderate swimming speed in order to avoid cold stress. These were: solving a short mathematic word problem, finding the hidden object in 2 picture puzzles, playing a memory game with the buddy and finding 13 objects that had been scattered on the ground beforehand. All subjects performed the same tasks. The accompanying adult-buddy was requested to avoid higher swimming speeds and extreme physical strain. The ascent was carried out at a maximum speed of 10 m min⁻¹ with a 3-min safety stop at the depth of 3 m.

Between the dives a 90-min surface interval was given.

As the subjects were required to put on and take off their diving equipment themselves, swim and, following the ascent, go to the examination room as quickly as possible, an equivalent physical activity was assumed compared to the actually existing conditions of an open water dive. For this reason, an active bubble provocation such as knee bends was not carried out.

Apart from the dive itself, the water exit and the walk to the examination room, the subjects were requested not to undergo physical strain up until the end of the investigations and to take care of sufficient liquid intake. In addition, the children were asked how they were feeling and they were encouraged to express any feeling of discomfort immediately.

Echocardiography

Bubble detection was conducted using the portable echocardiographic device Vivid i BT09 (GE Healthcare, Little Chalfont, Great Britain) equipped with a 3 S RS sector probe with an ultrasound frequency of 1.5–3.6 MHz. With the subjects in a left lateral resting position the apical 4 chamber view was located transthoracically by medical staff trained for ultrasound and recorded for 50 s. The heart rate of the subject was subsequently taken from the echocardiographic device Vivid i BT09 (GE Healthcare, Little Chalfont, Great Britain) and finally after 20 (t_d2-1 ) and 40 min (t_d2-2 ) after the second dive.

The reason for this shortened observation time was on the one hand the young age of the subjects and on the other hand that bubbles in such short and shallow dives were expected – if at all – only after the repeated dive. Furthermore, the probability of bubbles occurring late is reduced as the “slow” tissue (body compartments) are not at all or hardly saturated with nitrogen [2].

The time sequence of the test day is illustrated in ▶ Fig. 1.

Table 2  Number and type of diving licences of the subjects.

<table>
<thead>
<tr>
<th>Licence</th>
<th>Frequency</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic children’s diving licence</td>
<td>8</td>
<td>28.6</td>
</tr>
<tr>
<td>Intermediate children’s diving licence</td>
<td>6</td>
<td>21.4</td>
</tr>
<tr>
<td>Advanced children’s or basic adults’ diving licence ISO24801-1</td>
<td>10</td>
<td>35.7</td>
</tr>
<tr>
<td>Intermediate adults’ diving licence ISO24801-2</td>
<td>3</td>
<td>10.7</td>
</tr>
<tr>
<td>Advanced adults’ diving licence</td>
<td>1</td>
<td>3.6</td>
</tr>
<tr>
<td>Total</td>
<td>28</td>
<td>100</td>
</tr>
</tbody>
</table>

Bubble grading

The view and evaluation of a total of 150 echocardiographic videos was subsequently carried out anonymously by 2 experienced evaluation experts according to the expanded Eftedal-Brubakk scale [20] (▶ Table 3). Both right and left atriums and ventricles were examined. In case of obvious high bubble grades after the first dive, subjects were excluded from the second to avoid further complications.

For that RadiAnt DICOM Viewer (Medixant, Poznan, Poland) was used. Of these, further 15 selected videos were submitted to a different expert for grading. These included all bubble-positive videos as well as other randomly chosen ones. In the case of discrepancies, the videos were re-examined and discussed. On all cases with discrepancies final consensus could be reached.

Statistical evaluation

For the data description and evaluation, Microsoft Excel 15 (Microsoft Corporation, Redmond, USA) and IBM SPSS Statistics 24 (IBM Corporation Amonk, USA) were used.

The standard distribution of the anthropometric data was tested using the Shapiro-Wilk test. Differences between girls and boys were measured with a t-test for independent samples, and in the case of non-standard distribution data with a Mann-Whitney U test.

The results are shown as a mean value ± standard deviations.

Two groups were formed according to the ultrasound findings: children with and without observable bubbles after diving. The following potential influencing factors on the bubble formation were analysed: age, height, weight, BMI, body fat mass, muscle mass, physical activity, heart rate at the time of the ultrasound scan.


<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no observable bubbles</td>
</tr>
<tr>
<td>I</td>
<td>occasional bubbles</td>
</tr>
<tr>
<td>II</td>
<td>at least one new bubble every 4 cardiac cycles</td>
</tr>
<tr>
<td>III</td>
<td>at least one new bubble every cardiac cycle</td>
</tr>
<tr>
<td>IVa</td>
<td>at least one bubble · cm⁻² in every image</td>
</tr>
<tr>
<td>IVb</td>
<td>at least 3 bubbles · cm⁻² in every image</td>
</tr>
<tr>
<td>IVc</td>
<td>near whiteout; individual bubbles still discerned</td>
</tr>
<tr>
<td>V</td>
<td>whiteout; single bubbles cannot be discerned</td>
</tr>
</tbody>
</table>

▶ Fig. 1  Course of events on the examination day and illustration of the different points in time of the ultrasound examinations (US₁-₅) in regard to the dives: at rest (t_pre), within 10 min after first dive (t₁-1), within 10 min after second dive (t₁-2), 20 min after second dive (t₁-2), 40 min after second dive (t₂-2).
By means of a 2-sided Mann-Whitney U test the mean values of these were compared between the 2 groups.

Differences between the groups regarding the average heart rate at the different measurement times were examined by means of a 2-factor variance analysis with repeated measurements on one factor (at the point of measurement) and a Bonferroni test for multiple comparisons of means.

Finally, using binary logistic regression, a potential correlation was analysed between the factors age, height, weight and physical activity on bubble formation.

A p-value of <0.05 was considered significant.

Results

Bubble grades and symptoms

In all, 6 of 28 children were diagnosed with bubbles at different points in time after diving. The bubbles were solely located in the right atrium or ventricle respectively and no bubbles were traceable in the left atrium or ventricle. Furthermore, the bubble-positive children did not show any signs of DCS or other symptoms.

One participant showed bubbles with Grade III (▶Fig. 2) after the first dive. This subject was therefore excluded after the first dive. A statement about the correlation of bubble formation and repetitive dives cannot be made, since only children with Grade I bubbles repeated the dives and these Grade I bubbles follow no repetitive dives.

Grade I appeared in 5 of the 6 subjects, and in each case only in one of the recorded bubble videos (3 subjects showed Grade I after the first dive, whereas the other 2 presented with Grade I after the second dive). In previous and subsequent records these subjects showed Grade 0. Furthermore, their rating as Grade I was only apparent in the following analysis of the videos on the computer.

One participant showed bubbles with Grade III (▶Table 4) after the first dive. This subject was therefore excluded after the first dive and re-examined after 20 and 40 min. These scans showed Grade I. This was also only apparent in the following expert evaluation. In order to test the result for its reproducibility, that subject performed a further dive on a different day. Here, no bubbles occurred at any time (Grade 0).

Differences between the groups

With regard to the already named potential influencing factors there are no significant differences between the groups with and without bubbles (▶Table 5).

Also, the binary logistic regression analysis revealed no significant correlation between the factors (p>0.05; data not shown).

Table 4 Count of the detected bubble grades at rest (t_pre), within 10 min after first dive (t_{d1-1}), within 10 min after second dive (t_{d2-1}), 20 min after second dive (t_{d2-2}), 40 min after second dive (t_{d2-3}).

<table>
<thead>
<tr>
<th>Grade</th>
<th>t_pre</th>
<th>t_{d1-1}</th>
<th>t_{d2-1}</th>
<th>t_{d2-2}</th>
<th>t_{d2-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>28</td>
<td>24</td>
<td>27</td>
<td>27</td>
<td>25</td>
</tr>
<tr>
<td>I</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>III</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>28</td>
<td>28</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

Fig. 2 Echocardiographically detected Grade III in one subject, arrows point to single detected bubbles in the right atrium (RA). Also shown are the right ventricle (RV), the left atrium (LA) and the left ventricle (LV) without detected bubbles.

Discussion

To our knowledge, this is the first study which examines the occurrence of bubbles following standardised repeated dives in children.

Whilst small amounts of (non-symptomatic) circulating venous bubbles are common in adults [9] following deeper and longer dives than in this study, these were not observed Doppler-sonographically by Lemaître et al. after only one dive [16]. Neither the different detection method, nor the depth and duration of the dives in Lemaître’s study were directly comparable to the present study: the dives in Lemaître at al.’s study were not standardised for the subjects, who instead performed their usual dive. Hence, those children performed dives, that were 12±3 m deep for 26±7 min, which the authors referred to as “yo-yo dives”, because the subjects had ascended to or near the surface and had then descended several times during their dive. In contrast, our subjects stayed at the same depth for the whole dive. With regard to standardisation of dives, the current study follows the most restrictive German guidelines (VDST) for children’s diving in Germany at the time of the study (2016). In a maximum of 12-m depth the recommended bottom time for children (of 12–13 years) is 25 min and therefore much shorter than the time limit for no-decompression dives for this depth according to the common decompression guidelines and tables for adults (for example Deco 2000 [25]: the no-decompression limit for 12 m is 149 min). For this reason, it has until now been assumed that in children’s dives (our dives were merely 10 m deep) no bubble formation is to be expected, and so, only after the repeated dive. But with regard to this, hardly any research exists. Contrary to the previous assumption, in this study bubble formation was evidenced for 6 children at this depth and with a comparatively short dive time.

The subject with Grade III bubbles did not conduct a second dive. A statement about the correlation of bubble formation and repetitive dives cannot be made, since only children with Grade I bubbles repeated the dives and these Grade I bubbles follow no...
pattern. Subjects with bubbles after the first dive did not show any after the second dive and vice versa.

None of the children showed any symptoms of DCS after diving. This is in accordance with findings in adults [9], in which bubbles in the venous section do not necessarily result in the occurrence of DCS. Furthermore, the majority of the children with bubbles in our study showed a Grade I, which means occasional bubbles, hence also a single observed bubble. This can be evaluated as a low risk for DCS, as a Grade 0 is negatively predictive of DCS [8]. However, a higher bubble grade indicates a higher risk factor for the development of a DCS [11, 12].

It is assumed that some individuals are more susceptible to the production of bubbles than others [13]. According to Carturan et al. for instance, a more advanced age, weight, a higher body fat percentage as well as lower physical fitness do have an influence on bubble formation [4, 5]. Gialoni et al. recently also found that an increased BMI seems to increase bubbles [6]. Taking the small case number into consideration, this study, however, could not detect any potential influencing factors on bubble formation.

The difficulty to determine which individuals are more prone to bubble formation than others is maintained by the fact that the subject identified with Grade III did no longer show any bubbles in a dive one month later, even though the same examination protocol was followed. This indicates that the mechanisms of bubble formation are not trivial and in this case cannot be explained with the present information.

Finally, it should be stated that with these results no conclusions can be drawn as to which individuals have the tendency to bubble formation. For this, further studies with higher case numbers are required.

The occurrence of DCS in children and adolescents after shallow diving is not reported or not known. International case studies of diving accidents of young divers refer to adolescents over 14 years, who conducted dives exceeding the used depth limits in this study [7, 22]. However, the question regarding the clinical relevance of detected bubbles does remain, particularly with respect to them being a potential indicator for health risk in children. It is accepted that circulating venous bubbles are filtered out from the pulmonary circulation and expelled by breathing [24]. They can, however, lead to local damage in the sense of a classical DCS if they are generated directly in the tissue. In addition, there is a risk of them entering into the arterial system. The reason for an arterialisation can be a right-left-shunt as for example a patent foramen ovale (PFO). In the case of adults this is associated with the occurrence and the severity of a DCS [17]. But even without PFO or other cardiac shunts the (asymptomatic) arterialisation of bubbles (for example in the lung) could be observed [18, 19]. A crossover to the arterial system, however, arose only for very high bubble grades (≥ IV).

Arterialisation was not observed in our subjects. But since the clinical significance of bubbles in children remains unknown, and based on results from studies in adulthood occurring bubbles, represent a risk factor for DCS, diving for children should be executed in a conservative manner.

### Table 5
Level of significance of the differences in means of anthropometric data, sporting activity and heartrates during ultrasound examinations between the groups with and without bubbles after diving.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Group with bubbles after diving</th>
<th>Group without bubbles after diving</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>N</td>
</tr>
<tr>
<td>Female</td>
<td>1</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Male</td>
<td>5</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Age [years]</td>
<td>12.8</td>
<td>0.7</td>
<td>6</td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>51.4</td>
<td>10.7</td>
<td>6</td>
</tr>
<tr>
<td>Height [cm]</td>
<td>160.8</td>
<td>9.5</td>
<td>6</td>
</tr>
<tr>
<td>BMI [kg·m⁻²]</td>
<td>19.7</td>
<td>2.4</td>
<td>6</td>
</tr>
<tr>
<td>Body fat [%]</td>
<td>18.0</td>
<td>6.7</td>
<td>6</td>
</tr>
<tr>
<td>Muscle mass [%]</td>
<td>37.5</td>
<td>3.4</td>
<td>6</td>
</tr>
<tr>
<td>Reported physical exercise and sports [min·day⁻¹]</td>
<td>44.5</td>
<td>18.3</td>
<td>6</td>
</tr>
</tbody>
</table>

*p-level of significance is not depicted due to low number of cases; †the test of significance of Bonferroni showed a significant difference only between ‘at rest’ and ‘after first dive’

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The occurrence of DCS in children and adolescents after shallow diving is not reported or not known. International case studies of diving accidents of young divers refer to adolescents over 14 years, who conducted dives exceeding the used depth limits in this study [7, 22]. However, the question regarding the clinical relevance of detected bubbles does remain, particularly with respect to them being a potential indicator for health risk in children. It is accepted that circulating venous bubbles are filtered out from the pulmonary circulation and expelled by breathing [24]. They can, however, lead to local damage in the sense of a classical DCS if they are generated directly in the tissue. In addition, there is a risk of them entering into the arterial system. The reason for an arterialisation can be a right-left-shunt as for example a patent foramen ovale (PFO). In the case of adults this is associated with the occurrence and the severity of a DCS [17]. But even without PFO or other cardiac shunts the (asymptomatic) arterialisation of bubbles (for example in the lung) could be observed [18, 19]. A crossover to the arterial system, however, arose only for very high bubble grades (≥ IV).

Arterialisation was not observed in our subjects. But since the clinical significance of bubbles in children remains unknown, and based on results from studies in adulthood occurring bubbles, represent a risk factor for DCS, diving for children should be executed in a conservative manner.
Limitations

The echocardiographic scans of the 4-chamber apical view only represent a short snapshot of the potential bubbles in the blood circulation. Thus, the condition in other tissues cannot be imaged, however, circulating venous bubbles could provide evidence regarding the total bubble conditions in the body. Therefore, it is conceivable that far more bubbles could be present in other compartments of the body.

However, the achieved nitrogen saturation of each participant and therefore the nitrogen supersaturation in the “leading tissue” [6], was not calculated.

Furthermore, 2-dimensional echocardiography images only one section of a 3-dimensional space which means that single bubbles could have been missed during the records. Consequently, subjects with only sporadically detected bubbles could possibly have had more of these in the blood.

Using echocardiographic scans does not enable actual sizing of the detected bubbles [21], which also means that their risk of passing through the pulmonary circulation cannot be assessed.

The scans of this study were only recorded intermittently and do not reflect the actual process in the body meaning the whole period of time after an ascent up to the complete desaturation of nitrogen. In fact, bubble showers of short duration or bubbles occurring at a later stage could have been missed.

There were not as many ultrasound scans taken after the first dive as after the second one. That means that the bubble risk after the first dive cannot be sufficiently evaluated. In this way bubbles occurring subsequent to the first dive of the subjects could have been ignored.

To what extent, however, this discrepancy between the time intervals could have had an impact, remains currently only subject to speculation.

Once again, the present case number is too low to reveal potential influencing factors on bubble formation.

Conclusions

Children’s shallow dives also allow a tissue saturation with nitrogen which can generate bubbles. In this study only clinically inapparent bubbles were identified. However, we did not find reports of DCS in shallow dives of children and adolescents.

In spite of its high popularity and the enormous leisure value, the safety of children and adolescents while diving should take highest priority. Due to the existing uncertainty regarding the clinical relevance of bubbles, limitations are important. For that reason, an increase in the duration of the dive and maximum depth should be assessed very critically.

The decision regarding children’s diving remains a cautious and individual consideration, since so far there are no tools with which to sensibly assess bubble formation risk. Also, the diving behaviour, which includes repeating the dives or not, does not allow any conclusion regarding the formation of bubbles.

It requires longitudinally-designed studies with larger groups and standardised dives in order to understand and characterise the bubble generation in children better and to be able to evaluate the decompression risk.

Recommendations for Diving Practice with Young Divers

Since the results of this pilot study did not provide solid answers, the following recommendations are made as measures of precaution:

- Depth and time limits for children and adolescents should not be further increased. The minimum age limit for children diving should not be further reduced. Repetitive dives should be avoided. After dives a physical rest period is recommended.
- Parents and children should be thoroughly informed about the possibility of bubble formation and the potential risks emanating from this.

Acknowledgements

The authors would like to sincerely thank the children and adolescents and their parents for their participation in this study. Further thanks are due to Dr. med. Christian Beyer, Dr. med. Frank Hartig and the diving instructors and assistants during the research days. The study was supported by AC-INOX GmbH, Aqua Lung GmbH, BTs Europa AG, Medical Helpline Worldwide GmbH, Gesellschaft für Tauch- und Überdruckmedizin e.V., International Aquanautic Club GmbH & Co KG, monate mare Bäderbetriebsges. mbH, RSTC-Europe, Verband Deutscher Sporttaucher e.V. Partial results of the study were presented on the 4th of November 2017 at the 14th Scientific Symposium of the Society for Diving and Hyperbaric Medicine (Wissenschaftliche Tagung der Gesellschaft für Tauch- und Überdruckmedizin, GTÜM e.V.) at the Medical School of Hannover (Medizinische Hochschule Hannover) in Hannover, Germany.

Conflict of Interest

No conflict of interest has been declared by the authors.

References