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ORIGINAL ARTICLE

A new age-based equation for predicting maximum heart rate in endurance-trained runners



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Cardiovascular system;
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Abstract This study aimed to generate an age-based maximum heart rate (HR_{max}) equation for endurance-trained runners. Thirty-four male runners performed three tests on a motorized treadmill, starting at 8 km h^{-1} with increments of 1 km h^{-1} every 1, 2 or, 3 min. HR_{max} was defined as the highest heart rate value recorded during each test. *Post hoc* analyses indicated that the HR_{max} derived from each test was significantly lower than the highest HR_{max} value, for each participant. HR_{max} predicted by “ $206 - 0.7 \times \text{age}$ ” underestimated the highest HR_{max} by $8.6 \text{ beats min}^{-1}$. Thus, the generated age-based “ $218 - 0.8 \times \text{age}$ ” equation should be used to predict HR_{max} in endurance-trained runners.

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PALAVRAS-CHAVE

Sistema cardiovascular;
Teste físico;
Resistência física;
Corrida

Uma nova equação baseada em idade para predição da frequência cardíaca máxima em corredores aerobiamente treinados

Resumo Esse estudo objetivou gerar uma equação de frequência cardíaca máxima (FC_{max}) baseada na idade para corredores aerobiamente treinados. Trinta e quatro corredores homens realizaram três testes incrementais em esteira motorizada, com início a $8 \text{ km} \cdot \text{h}^{-1}$ e incrementos de $1 \text{ km} \cdot \text{h}^{-1}$ a cada um, dois ou, três minutos. A FC_{max} foi definida como o valor mais alto de frequência cardíaca registrado em cada teste. As análises de *post hoc* indicaram que a FC_{max} de cada teste foi significativamente menor que o valor mais elevado de FC_{max} para cada

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PALABRAS CLAVE

Sistema cardiovascular;
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Carrera

participante. A FC_{\max} predita pela equação “ $206 - 0,7 \times \text{idade}$ ” subestimou a mais alta FC_{\max} em 8,6 batimentos·min⁻¹. Logo, a equação gerada baseada em idade “ $218 - 0,8 \times \text{idade}$ ” deveria ser usada para prever a FC_{\max} em corredores aerobiamente treinados.

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Una nueva ecuación basada en la edad para pronosticar la frecuencia cardíaca máxima en corredores entrenados en resistencia

Resumen El objetivo de este estudio fue generar una ecuación de la frecuencia cardíaca máxima (FC_{\max}) basada en la edad en corredores entrenados en resistencia. Treinta y cuatro corredores de sexo masculino realizaron 3 pruebas en una cinta ergométrica motorizada, comenzando con la velocidad de 8 km/h⁻¹ con incrementos de 1 km/h⁻¹ cada uno, 2 o 3 min. La FC_{\max} fue definida como el valor de la frecuencia cardíaca más elevada registrada durante cada prueba. Los análisis posteriores indicaron que la FC_{\max} derivada de las pruebas fue considerablemente más baja que el valor más alto de la FC_{\max} de cada participante. La FC_{\max} pronosticada por la ecuación « $206-0,7 \times \text{edad}$ », subestimada la más alta FC_{\max} por 8,6 lat/min⁻¹. Así, la ecuación generada basada en la edad « $218-0,8 \times \text{edad}$ » debería utilizarse para pronosticar la FC_{\max} en corredores entrenados en resistencia.

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Introduction

Maximal heart rate (HR_{\max}) is one of the most commonly used values in clinical medicine and physiology (Tanaka et al., 2001) where it is used as a criterion for assessing maximal effort during graded exercise testing (Duncan et al., 1997; Howley et al., 1995) and can be used to prescribe appropriate exercise intensity (ACSM, 2006; Robergs and Landwehr, 2002). For these purposes, exercise and fitness professionals often use age-based equations to estimate HR_{\max} (Engels et al., 1998; Sporis et al., 2011; Tanaka et al., 2001). However, several equations are available to estimate this value (Engels et al., 1998; Gellish et al., 2007; Graettinger et al., 1995; Inbar et al., 1994; Jones et al., 1985; Lester et al., 1968; Miller et al., 1993; Schiller et al., 2001; Sheffield et al., 1978; Tanaka et al., 1997; Whaley et al., 1992), including meta-analyses of published equations (Londeree and Moeschberger, 1982; Tanaka et al., 2001) and most of them differ widely in their estimates of HR_{\max} (Londeree and Moeschberger, 1982). Additionally, these equations were derived from different populations and testing protocols, which can also affect the determination of this value.

HR_{\max} is a protocol-dependent physiological variable that is expected to be higher in long-duration tests as compared to short-duration tests (Bishop et al., 1998; Roffey et al., 2007). Nevertheless, some age-based HR_{\max} equations were generated using short protocols (Graettinger et al., 1995; Inbar et al., 1994; Schiller et al., 2001; Tanaka et al., 1997), following the suggestion of Buchfuhrer et al. (1983) to bring the subject to the limit of tolerance in 10 ± 2 min. In fact, Buchfuhrer et al. (1983) suggested that short duration protocols were best to obtain the highest maximal oxygen uptake ($VO_{2\max}$) value, but not for attaining the highest

HR_{\max} value. This group also reported higher HR_{\max} values in long (~26 min) tests than in short (~11 min) tests. These reports, therefore, suggest that age-based HR_{\max} equations were generated using testing protocols that might not have been the most appropriate for attaining the highest value for HR_{\max} . Additionally, one other shortcoming of the currently available age-based equations is that none of the previous studies derived a predictive equation by using the highest HR_{\max} value obtained from two or more testing protocols, using the same individuals. Such a method could provide higher values for each subject and, consequently, higher values for the derived HR_{\max} equation.

The incorrect prediction of HR_{\max} may cause systematic errors in exercise prescriptions (Cleary et al., 2011). When HR_{\max} is overestimated, the prescribed exercise intensity will be greater than needed to improve cardiovascular fitness. On the other hand, the underestimation of HR_{\max} leads to lower stimulus that may not improve aerobic parameters. Thus, reducing the error associated with estimating HR_{\max} would improve the accuracy of exercise prescriptions (Cleary et al., 2011), and improved estimates require the development and use of new equations designed for specific populations and modes of exercise (Robergs and Landwehr, 2002). Thus, the purpose of this study was threefold: (a) to compare three age-based HR_{\max} equations derived for the same participants from each incremental test of different duration, (b) to derive an age-based HR_{\max} equation for recreational endurance-trained runners from the highest HR_{\max} value, for each participant, attained from the three incremental tests, and (c) to compare the generated equations with the well-known “ $206 - 0.7 \times \text{age}$ ” equation proposed by Tanaka et al. (2001) for recreational endurance-trained individuals. We hypothesized that the

“ $206 - 0.7 \times \text{age}$ ” equation would underestimate the highest HR_{max} values obtained by the current protocol for recreational endurance-trained runners.

Materials and methods

Participants

Thirty-four male, recreational, endurance-trained runners of regional and local level with a minimum of two years of training experience volunteered to take part in this study. The 10-km running times of the participants were between 35 and 60 min, with a pace between 10 and 17 km h^{-1} (~45–75% of the world record). Prior to testing, all participants provided written informed consent and the local ethics committee approved the experimental protocol (#719/2010).

Experimental overview

In a counterbalanced order, participants who were habituated to running tests performed three continuous incremental exercise tests of different stage durations on a motorized treadmill (Super ATL; Inbrasport, Porto Alegre, Brazil), with the gradient set at 1%. The tests were performed over two weeks, with each test separated from the other by at least 48 h. The three different stage duration protocols were as follows: (a) short stage duration of 1 min (SS), (b) intermediate stage duration of 2 min (IS), and (c) long stage duration of 3 min (LS).

Exercise protocols

After a warm-up that consisted of walking at 6 km h^{-1} for 3 min, each protocol started with an initial speed of 8 km h^{-1} , followed by an increase of 1 km h^{-1} between each successive stage until volitional exhaustion. The speed was increased every 1 min for the SS test, every 2 min for the IS test, and every 3 min for the LS test. Consistently across each trial, participants were strongly encouraged, verbally to invest maximum effort. All the three tests were performed at the same time of the day, under normal laboratory conditions (temperature = $20\text{--}22^\circ\text{C}$ and relative humidity = 50–60%). Participants were instructed to report for testing well-rested, nourished, and hydrated, wearing lightweight comfortable clothing. Participants were also instructed to avoid eating 2 h before the maximal exercise tests, to abstain from caffeine and alcohol, and to refrain from strenuous exercise for 24 h before testing.

Physiological variables

Before testing, participants were familiarized with the 6–20 scale by Borg (1982), which was used to measure the rating of perceived exertion (RPE) during the last 15 s of each stage and at exhaustion. The highest RPE value was adopted as the peak RPE (RPE_{peak}). Heart rate (HR) was recorded every five seconds throughout the tests (Polar RS800sd, Kempele, Finland) and HR_{max} was defined as the highest HR value

Table 1 Characteristics of the participants and training.

Variables	Mean \pm SD
Age (years)	40.1 \pm 12.8
Body mass (kg)	67.7 \pm 7.2
Height (cm)	173.3 \pm 7.0
Body mass index (kg m^{-2})	22.5 \pm 1.8
Training frequency (days wk^{-1})	4.9 \pm 1.5
Training distance (km wk^{-1})	58.5 \pm 31.7
<i>n</i> = 30.	

recorded during the test (Bentley and McNaughton, 2003; Schiller et al., 2001; Tanaka et al., 2001). Neither respiratory gases nor blood lactate were monitored during the tests concerning that such interventions would affect the performance of the participants (Schabert et al., 1998). Earlobe capillary blood samples ($25 \mu\text{L}$) was collected into a glass tube at the end of the tests and at the third, fifth, and seventh minute of passive recovery, sitting in a comfortable chair. From these samples, blood lactate concentration was subsequently determined by electroenzymatic methods using an automated analyzer (YSI 2300 STAT, Ohio, USA). Peak blood lactate concentration (LA_{peak}) was defined for each participant as the highest post-exercise blood lactate concentration value. The maximal effort was deemed to be achieved if the incremental test met two of the following criteria: 1) LA_{peak} higher than 8 mmol L^{-1} , 2) HR_{max} within $\pm 10 \text{ beats min}^{-1}$ of endurance-trained age-predicted HR_{max} using the age-based “ $206 - 0.7 \times \text{age}$ ” equation (Tanaka et al., 2001) and 3) RPE_{peak} greater than 18 in the 6–20 Borg scale (Howley et al., 1995).

Statistical analyses

Data are presented as mean \pm SD and were analyzed using the SPSS 17.0 software. The Shapiro–Wilk test was used to check the normality of the data distribution. HR_{max} values were compared using repeated measures ANOVA with Bonferroni *post hoc* test. The sphericity assumption was checked by Mauchly’s test of sphericity. A simple linear regression was employed to determine the age-based HR_{max} equation from the SS (HR_{maxSS}), IS (HR_{maxIS}) and LS (HR_{maxLS}) tests. Additionally, an age-based HR_{max} equation was derived from the highest HR_{max} value attained for each participant from the SS, IS, and LS tests ($\text{HR}_{\text{maxSIL}}$). The relationship between HR_{max} and age was examined using the Pearson’s correlation coefficient (*r*), the coefficient of determination (R^2) and the standard error of estimate (SEE). Statistical significance was set at $p < 0.05$.

Results

The characteristics of the participants (mean \pm SD) are presented in Table 1.

Four participants did not meet at least two criteria of maximal effort in at least one test. The tests from these participants were not included in the results. The summary of the physiological parameters of the remaining thirty participants (mean \pm SD) is given in Table 2. Analysis of variance revealed a significant effect of the stage duration on

Table 2 Values of maximum rating of perceived exertion (RPE_{peak}), peak blood lactate concentration (LA_{peak}), percentage of age-predicted maximum heart rate (%APMHR), and maximal heart rate (HR_{max}) during treadmill incremental protocols with stage length of 1 min (SS), 2 min (IS) and 3 min (LS).

Protocol	RPE _{peak} (6–20 Borg scale)	LA _{peak} (mmol L ⁻¹)	%APMHR (%)	Time to exhaustion (min)	HR _{max} (beats min ⁻¹)
SS	19.8 ± 0.6	9.4 ± 2.2	102.3 ± 4.0	11.1 ± 1.6	181.8 ± 12.1
IS	19.8 ± 0.4	9.2 ± 1.9	104.0 ± 4.3 ^a	19.4 ± 3.0 ^a	184.8 ± 12.7 ^a
LS	19.9 ± 0.4	7.9 ± 2.2 ^a	103.0 ± 4.1 ^a	26.7 ± 4.7 ^{a,b}	183.1 ± 12.9
SIL	20.0 ± 0.0	10.3 ± 2.0 ^{a,b,c}	104.8 ± 4.1 ^{a,b,c}	–	186.3 ± 12.7 ^{a,b,c}

Values are means ± SD, *n* = 30. SIL, highest values attained for each participant from the SS, IS and LS protocols.

^a *p* < 0.05 compared with the SS protocol.

^b *p* < 0.05 compared with the IS protocol.

^c *p* < 0.05 compared with the LS protocol.

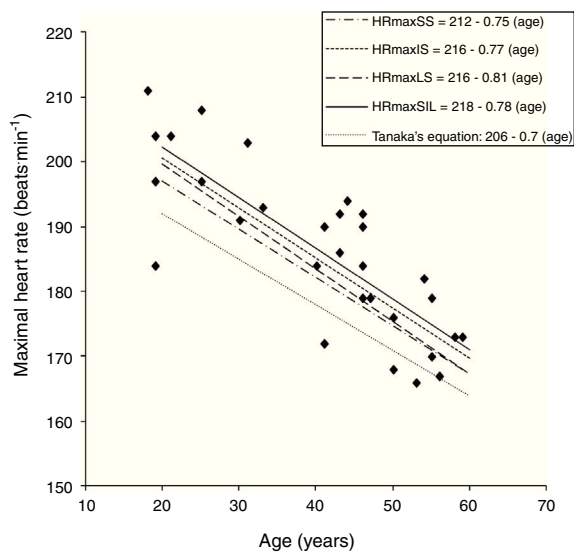


Figure 1 Comparison between age-based maximal heart rate equations derived from incremental protocols with stage length of 1 min (HR_{max}SS), 2 min (HR_{max}IS) and 3 min (HR_{max}LS). It also presents the proposed HR_{max}SIL equation from the highest maximal heart rate value attained for each participant from the three tests of different stage duration and the meta-analysis equation “206 – 0.7 × age” for endurance-trained individuals.

the LA_{peak} (*p* = 0.001), percentage of endurance-trained age-predicted HR_{max} (*p* = 0.003), time to exhaustion (*p* < 0.001) and HR_{max} (*p* = 0.003). The RPE_{peak} did not significantly differ among the three protocols (*p* = 0.36). *Post hoc* analyses indicated that the HR_{max}SIL was significantly higher than the HR_{max} derived from the SS, IS or LS tests (*p* < 0.001).

Fig. 1 presents the measured HR_{max} (*i.e.*, the highest HR_{max} values attained for each participant from the SS, IS, and LS tests) and the age-based HR_{max} equations from the SS (HR_{max}SS), IS (HR_{max}IS) and LS (HR_{max}LS) tests. Further, it presents the proposed HR_{max}SIL equation from the measured HR_{max} and the “206 – 0.7 × age” meta-analysis equation proposed by Tanaka et al. (2001). In developing the HR_{max}SIL equation from the three protocols, the IS protocol contributed with 56.7% of the HR_{max} values. The LS and SS protocols contributed with 33.3% and 10.0%, respectively. The correlation coefficient, coefficient of determination and standard error of

estimate of the generated “218 – 0.8 × age” equation were *r* = –0.81; *R*² = 0.66, and SEE = 7.5 beats min⁻¹. The relative SEE (*i.e.*, SEE expressed as a percentage of the mean of the outcome measure) was 4.1%. The HR_{max} predicted by the “206 – 0.7 × age” equation was 177.7 ± 9.2 beats min⁻¹ and, on average, according to repeated measures ANOVA, underestimated the measured HR_{max} by 8.6 beats min⁻¹ in the present population.

Discussion

The main purpose of the present study was to derive an age-based HR_{max} equation for recreational endurance-trained runners. The main finding was that the generated “218 – 0.8 × age” equation should be used to predict HR_{max} in endurance-trained runners rather than the well-known “206 – 0.7 × age” meta-analysis equation by Tanaka et al. (2001). In fact, the “206 – 0.7 × age” equation, on average, underestimated the highest HR_{max} values by 8.6 beats min⁻¹.

The incorrect prediction of HR_{max} may cause systematic errors in exercise prescriptions (Tanaka et al., 2001). When the HR_{max} is overestimated, the prescribed exercise intensity will be greater than needed to improve cardiovascular fitness. On the other hand, the underestimation of HR_{max} leads to lower stimulus that possibly will not improve aerobic parameters. Reducing the error of estimating HR_{max} would improve the accuracy of exercise prescription (Cleary et al., 2011). Consequently, several studies have been conducted to generate new age-based HR_{max} equations to estimate the HR_{max} more accurately (Engels et al., 1998; Gellish et al., 2007; Graettinger et al., 1995; Inbar et al., 1994; Jones et al., 1985; Lester et al., 1968; Londeree and Moeschberger, 1982; Miller et al., 1993; Schiller et al., 2001; Sheffield et al., 1978; Tanaka et al., 1997, 2001; Whaley et al., 1992). Nevertheless, most of them are too general or unspecific for the population of endurance-trained runners.

Tanaka et al. (2001) presented one of the most usual equations to predict HR_{max} (Cleary et al., 2011; Franckowiak et al., 2011). They proposed the general age-based “208 – 0.7 × age” equation, independent of gender and habitual physical activity status, which was generated by a meta-analytic study that included 351 studies involving 18,712 individuals. This general equation is valid for heterogeneous groups within a wide age range including children and adolescents (Machado and Denadai, 2011). They also proposed the equation “206 – 0.7 × age” for the specific

population of endurance-trained individuals. Nevertheless, in contrast to some studies (Camarda et al., 2008; Cleary et al., 2011; Silva et al., 2007), we found that the specific “ $206 - 0.7 \times \text{age}$ ” equation underestimated the actual HR_{max} in endurance-trained runners.

Camarda et al. (2008), for example, analyzed the data from 2047 sedentary individuals (age, 12–69 years), and reported that the HR_{max} obtained by the “ $208 - 0.7 \times \text{age}$ ” equation ($182.7 \pm 8.2 \text{ beats min}^{-1}$) overestimated the measured HR_{max} ($180.8 \pm 13.8 \text{ beats min}^{-1}$). Similarly, Cleary et al. (2011) evaluated 96 active subjects ranging from 18 to 33 years old. They found that the general “ $208 - 0.7 \times \text{age}$ ” equation overestimated the measured HR_{max} (192.6 ± 1.9 and $190.1 \pm 7.9 \text{ beats min}^{-1}$, respectively). Silva et al. (2007) assessed 93 elderly women (age, 67 ± 5 years) during the modified Bruce protocol and found that the measured HR_{max} ($145.5 \pm 12.5 \text{ beats min}^{-1}$) was highly overestimated by the general “ $208 - 0.7 \times \text{age}$ ” equation ($161.0 \pm 3.9 \text{ beats min}^{-1}$). On the other hand, we found that the specific “ $206 - 0.7 \times \text{age}$ ” equation for endurance-trained runners underestimated the actual HR_{max} for the sample of this study. Supporting our results, Sporis et al. (2011), assessed 509 members of the Croatian Armed Forces (age, 29.1 ± 5.5 years) and concluded that the general “ $208 - 0.7 \times \text{age}$ ” equation underestimates the actual HR_{max} value by $4.2 \text{ beats min}^{-1}$ in military personnel. Similarly, Nes et al. (2013) examined the relationship between HR_{max} and age in 3320 healthy individuals within a wide age range (19–89 years) and reported that the “ $208 - 0.7 \times \text{age}$ ” equation underestimated the measured HR_{max} by $6.2 \text{ beats min}^{-1}$ even using an individualized protocol that brought the subjects to exhaustion within 8–12 min.

An important factor to develop an accurate age-based HR_{max} equation for a specific population is the homogeneity of the sample. This study involved 34 recreational endurance-trained runners. The small number of participants was the main limitation of this study. However, the difficulty in obtaining a homogeneous group of participants willing to perform three running tests in laboratory until exhaustion was a factor that restricted the sample size. In contrast, the sample of this study ranged widely in age, contributing to the generation of the equation. Another factor that influences the accuracy of a generated age-based HR_{max} equation is the duration of the incremental test. Roffey et al. (2007) showed that the HR_{max} was significantly higher during long ($25 \pm 4 \text{ min}$) incremental tests than it was in shorter tests ($10 \pm 2 \text{ min}$). Moreover, Bishop et al. (1998) found significantly higher values for HR_{max} when a stage duration of 3 min was used, rather than 1 min, during incremental tests. Thus, the design of the incremental tests might have affected most of the available age-based HR_{max} equations.

In this study, the age-based equation generated from IS protocol was the most similar to the $\text{HR}_{\text{max}}\text{SIL}$ equation (Fig. 1) and contributed with about 60% of the data for its generation. Additionally, not only the $\text{HR}_{\text{max}}\text{SIL}$ but also all the three equations generated from just one test (*i.e.*, $\text{HR}_{\text{max}}\text{SS}$, $\text{HR}_{\text{max}}\text{IS}$ and $\text{HR}_{\text{max}}\text{LS}$) presented higher values for HR_{max} than the “ $206 - 0.7 \times \text{age}$ ” equation. Further, the “ $206 - 0.7 \times \text{age}$ ” equation, on average, underestimated the measured HR_{max} values by $8.6 \text{ beats min}^{-1}$ in the recreational endurance-trained population. Thus, the proposed

“ $218 - 0.8 \times \text{age}$ ” equation, generated from three incremental tests of different durations, seems to be more appropriate for predicting HR_{max} in this population of runners.

The majority of age-based univariate equation for predicting HR_{max} have large errors between 7 and 11 beats min^{-1} (Robergs and Landwehr, 2002). Further, according to these authors, equations need to be developed that are population specific. The error of the proposed “ $218 - 0.8 \times \text{age}$ ” equation for the specific population of recreational endurance-trained runners was relatively low, and in accordance with previous studies. Nes et al. (2013), for example, proposed recently the “ $211 - 0.64 \times \text{age}$ ” equation to predict the HR_{max} in healthy individuals and reported a higher, but also in accordance with previous studies, error (*i.e.*, $\text{SEE} = 10.8 \text{ beats min}^{-1}$; $r = -0.60$). Nevertheless, due to the inherent error associated with the estimation of HR_{max} , using the proposed “ $218 - 0.8 \times \text{age}$ ” equation, approximately 67% of the population should fall within $\pm 8 \text{ beats min}^{-1}$ of the actual HR_{max} . Further, for 5% of the population, the actual HR_{max} could differ by more than $15 \text{ beats min}^{-1}$. Therefore, direct measurements of HR_{max} should be used whenever possible.

Although this study adds important value to the literature as well as present great practical application, it also has a limitation. Due to the specific characteristics of the sample (recreational endurance-trained runners), our sample size is small for this type of study. However, as mentioned, the equation was built to provide a great practical application for this specific population.

Conclusion

In summary, the results from the present study suggest that the proposed “ $218 - 0.8 \times \text{age}$ ” equation should be used to predict HR_{max} in recreational endurance-trained runners rather than the well-known “ $206 - 0.7 \times \text{age}$ ” equation proposed by Tanaka et al. (2001). Additionally, the “ $206 - 0.7 \times \text{age}$ ” equation, on average, underestimated the measured HR_{max} values by $8.6 \text{ beats min}^{-1}$ in the recreational endurance-trained population. Researchers, coaches, and practitioners are recommended to use this formula to determine HR_{max} more accurately in endurance-trained runners. Because the results of this study are limited to this specific population, further research is warranted to verify whether these results apply to other populations that have different performance levels.

Ethical statement

Comite de Ética e Pesquisa em Seres Humanos, Universidade Estadual de Maringá (#1.262.502/2015).

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Conflicts of interest

The authors declare no conflicts of interest.

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