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ORIGINAL ARTICLE

The influence of caffeine on energy content of sugar-sweetened beverages: 'the caffeine–calorie effect'

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Background/Objectives: Caffeine is a mildly addictive psychoactive chemical and controversial additive to sugar-sweetened beverages (SSBs). The objective of this study is to assess if removal of caffeine from SSBs allows co-removal of sucrose (energy) without affecting flavour of SSBs, and if removal of caffeine could potentially affect population weight gain.

Subjects/Methods: The research comprised of three studies; study 1 used three-alternate forced choice and paired comparison tests to establish detection thresholds for caffeine in water and sucrose solution (subjects, $n=63$), and to determine if caffeine suppressed sweetness. Study 2 (subjects, $n=30$) examined the proportion of sucrose that could be co-removed with caffeine from SSBs without affecting the flavour of the SSBs. Study 3 applied validated coefficients to estimate the impact on the weight of the United States population if there was no caffeine in SSBs.

Results: Detection threshold for caffeine in water was higher (1.09 ± 0.08 mM) than the detection threshold for caffeine in sucrose solution (0.49 ± 0.04 mM), and a paired comparison test revealed caffeine significantly reduced the sweetness of sucrose ($P<0.001$). Removing caffeine from SSBs allowed co-removal of 10.3% sucrose without affecting flavour of the SSBs, equating to 116 kJ per 500 ml serving. The effect of this on body weight in adults and children would be 0.600 and 0.142 kg, which are equivalent to 2.08 and 1.10 years of observed existing trends in weight gain, respectively.

Conclusion: These data suggest the extra energy in SSBs as a result of caffeine's effect on sweetness may be associated with adult and child weight gain.

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Keywords: obesity; threshold; flavour; soft drinks

Introduction

Caffeine is a controversial food additive due to its mildly addictive properties, which aide development of flavour preferences (Sun, 1980; Griffiths and Woodson, 1988; Griffiths and Vernotica, 2000; Yeomans *et al.*, 2000; Keast and Riddell, 2007). The mode of action of caffeine in developing flavour preference is not immediate (Yeomans *et al.*, 2000) as, for example, we experience with a sucrose solution (sweet and appetitive). Caffeine may elicit no perceived flavour or bitterness in the mouth depending on concentration (Keast and Roper, 2007), but the positive affects occur post-consumption with increased vigilance and attention, enhanced mood and arousal as well as enhanced motor activity. Behavioural studies have shown that the consumption of caffeine promotes a dependence that is reinforced with repeat consumption (Hughes *et al.*, 1993; Schuh and Griffiths, 1997; Garrett and Griffiths, 1998). The common method of repeat caffeine consumption is via caffeinated foods such as coffee, tea, cocoa and soft drinks, which are hedonically pleasant to drink. Soft drink manufacturers claim caffeine is added to sugar-sweetened beverages (SSBs) as a flavouring agent (PepsiCo, 1981). In theory it should be easier to detect caffeine in water than a more complex vehicle such as a sweet solution or SSBs, due to lower noise or the higher signal to noise ratio in water. Evidence from previous work in our laboratory indicated that caffeine, at concentrations in SSBs, can be identified in sweet solution but not in water (Keast and Riddell, 2007;

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Keast and Roper, 2007). This appears counterintuitive, as the increased noise of the sweet solution should dilute the caffeine signal, unless caffeine was affecting the 'noise' and subjects could identify the caffeine signal via differences in sweetness.

SSBs are micro-nutrient void, energy containing, readily-available beverages that are consumed in large quantities around the world with Americans being particularly high consumers (Datamonitor, 2007). Regular SSBs consumers have higher energy intakes (up to 10%) than non-consumers (Ludwig *et al.*, 2001; Krachler *et al.*, 2006; Striegel-Moore *et al.*, 2006). Overall there is a strong link between over-consumption of SSBs, higher energy intake and development of overweight and obesity (Troiano *et al.*, 2000; Ebbeling *et al.*, 2006). If caffeine was suppressing sweetness in SSBs, then extra sugar must be added to maintain equivalent sweetness. Additionally, consumption of SSB has been implicated in displacement of more nutritious foods in adolescents (McGartland *et al.*, 2003).

The study examined whether the removal of caffeine from SSBs would allow co-removal of the sweetener thereby decreasing the energy content of the SSBs. We investigated this by the following: (1) establishing detection thresholds for caffeine in water and sucrose, (2) assessing if caffeine, in levels found in common cola beverages, affects sweetness of sucrose, (3) determining how much sucrose could be co-removed with caffeine without noticeable difference in flavour of SSBs, and (4) calculating the 'caffeine–calorie' effect of energy reduction on secular (observed existing trend) population weight gain.

Subjects and methods

Study design
The study consisted of three parts. Study 1 was designed to determine detection thresholds for caffeine in water and sucrose solution, and to determine if caffeine, at usual SSB concentrations suppressed sweetness. Study 2 assessed whether removal of caffeine from SSBs allowed co-removal of sucrose, without affecting flavour of the SSBs. In both study 1 and 2 a minimum of 30 subjects was required to approximate a normal population distribution (Tijms, 2004). Study 3 estimated the influence of the extra energy as a result of caffeine in SSBs on population weight gain.

All studies were conducted in a specialized sensory-testing facility comprising of seven individual booths under red light and using Compusense five 4.6 (Compusense, Guelph, Canada) data collection program. Each subject was isolated from other subjects by vertical dividers and there was no interaction between subjects. All subjects were regular caffeine consumers and were asked to refrain from eating, drinking or chewing gum for 1 h before testing and all agreed to participate and provided informed consent on an approved Deakin University Human Ethics Review Board form. The results from study 2 were used in study 3 to model the influence of caffeine on weight gain at the population level.

Stimuli and delivery
Food grade caffeine was purchased from Sigma Chemical (St Louis, MO, USA) and sucrose was purchased from Pure Australian white sugar resources. Lemon, apple and raspberry odours were purchased from Specialty Flavors & Fragrances Co. (Melbourne, VIC, Australia); citric acid was purchased from Brewer's Den (Boronia, VIC, Australia). Aqueous solutions were freshly prepared every day, using filtered (fi) water (8 μm particulate filter plus an activated charcoal filter, DURA, 3M Purification Pty Ltd, Pymble, New South Wales, Australia), several hours in advance of testing. Model soft drinks were prepared freshly in the Deakin University food laboratories, and stored in 5 l bottles in the laboratory refrigerator. The soft drink composition was similar to commercially available sugar-sweetened soft drink: 0.67 mM caffeine, 321 mM sucrose, 4.7 mM citric acid, 0.2% flavourings. The flavour was complex fruity to avoid any expectations that may be associated with cola or other easily recognized flavours. Water (fi) was used as the blank stimulus and as rinsing agent in all experiments. Sucrose concentration was set at 204 mM in experiments 1 and 2 because it has been shown to be equi-sweet to common cola beverages (Keast and Riddell, 2007). In experiment 3, 321 mM sucrose was used as it is the concentration in a common cola beverage. In experiments 2 and 3, caffeine concentration was set at 0.67 mM because it is the concentration in a common cola beverage. Samples (20 ml) were served at room temperature (20 ± 3 °C) in 30 ml plastic medicine cups (McFarlane Medical and Scientific, Melbourne, VIC, Australia). Room temperature was used to avoid any confounding effects that may be caused by cooling samples (Green and Frankmann, 1988).

Study 1a: detection threshold determination of caffeine in water and sucrose
Study 1 outline. Subjects were studied on five separate occasions. Four occasions were to determine caffeine detection thresholds in water and sucrose solution, in duplicate. The final occasion was a paired comparison test to assess if caffeine, at concentration in common SSBs, suppressed the sweetness of sucrose.

Caffeine detection thresholds. Subjects ($n = 63$, 22 ± 4 years old, 59 female) between the ages of 18 and 41 were recruited via public advertising around Deakin University Melbourne, Australia. The range of caffeine concentrations used was modified from the ISO method for investigating sensitivity of taste (16 step dilution series: 0.03, 0.08, 0.18, 0.28, 0.33, 0.42, 0.52, 0.66, 0.8, 1.03, 1.3, 1.57, 1.84, 2.11, 2.38, 2.65 mM caffeine). A triangle forced-choice ascending method of limits was performed in triplicate for each caffeine concentration and used to determine if subjects could discriminate between the control and caffeinated samples. The order of presentation was randomized and could have been any of three possible orders (A/ caffeinated and B/ non-caffeinated): BBA, BAB, and ABB. If subjects identified incorrectly, they were presented with a set of samples containing the next higher level of caffeine. There was an inter set interval of ~60 s, during which time subjects were instructed to rinse with water at least three times. Subjects wore nose clips to eliminate olfactory cues when sampling and were asked to choose the sample that was different from the others. The test was completed when they correctly identified the odd sample at a particular level of caffeine three consecutive times. The chance of correctly guessing three in a row was 3.7%.

Study 1b: effect of caffeine on sweetness

Subjects were recruited from experiment 1 ($n=23$, age 22 ± 4 years old, 18 female) and assessed the effects of caffeine on sweetness using a directional paired comparison test. Sucrose solution (204 mM) or caffeine (0.67 mM) + sucrose solution (204 mM) mixture was used as stimuli and subjects were asked which of the two samples was sweeter. The test was performed in triplicate and the order of presentation was randomized. All experimental conditions were as previously stated.

Study 2: magnitude of sweetness reduction by caffeine

Study outline. A just noticeable difference assesses the potential reduction of a single ingredient in food before there is a noticeable difference. In general, just noticeable differences for sucrose is ~10% (McBride, 1983), that is the concentration can be reduced by 10% before sweetness is perceiveably affected. In this experiment we determined the potential amount of sucrose that could be removed from SSB when caffeine was removed, without affecting flavour.

Subject screening. Subjects ($n=106$, 31 ± 1 years, 72 female) between the ages of 20 and 65 were screened over three separate sessions following International Standards Organisation 8586-1 'General guidance for selection, training, and monitoring of assessors'. Thirty subjects (32 ± 2 years, 19 female) were chosen to complete this study based on their ability to detect small changes in flavour.

Just noticeable difference test. A directional paired comparison test was used to examine how much sugar could be co-removed with caffeine from SSBs without a perceivable difference in flavour. Six sessions on separate days were performed using caffeinated and non-caffeinated beverage. In any one session, two sample pairs were assessed (see Figure 1 for design). To start each session, within each sample pair one solution contained 321 mM sucrose solution and the other contained 315 mM sucrose. Subjects were asked to pick which was sweeter. If they answered correctly (321 mM), they were given the identical samples (321 vs 315 mM in random order; A B or B A) and asked the same question. If they answered incorrectly they would test the next lower concentration of sucrose (321 vs 309 mM). The method would continue until there were four correct identifications of 321 mM sucrose sample compared with the variable concentration sucrose sample. The chance of correctly guessing four in a row was 6.25%. Subjects did not wear nose clips, however, all other experimental conditions were as previously stated.

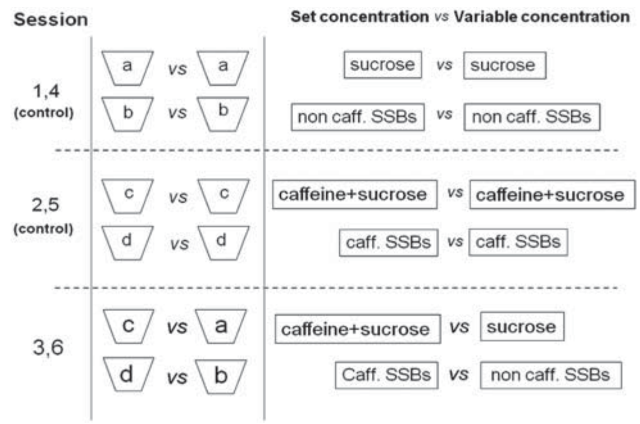

Figure 1 Magnitude of sweetness-reduction experimental design. Directional paired comparison test for variation in sweetness in caffeinated and non-caffeinated sucrose and SSB. Set concentration = 321 mM sucrose; variable concentration = 315, 309, 303, 297, 291, 285, 279, 273 mM sucrose. Session 1, 2, 4 and 5 are controls where identical solutions except for varying sucrose concentration are compared with each other. Session 3 and 6 compares caffeinated versus non-caffeinated solutions with varying sucrose solutions.

Statistical analysis

Difference in detection threshold for caffeine between water and sucrose was determined with a paired samples *t*-test. The effect of caffeine on sweetness was assessed using triangle test for difference table (Meilgaard *et al*., 2007). For all statistical analyses, SPSS (Version 15, SPSS Inc., Chicago, IL, USA) was used. *P*-values <0.05 were considered statistically significant.

For any individual, the non-perceivable difference in sucrose reduction was determined as the geometric mean of the concentration correctly identified and the last incorrect concentration. There is wide variation in oral sensitivity to caffeine and sweetness within the population (Delwiche *et al*., 2001; Hayes and Duffy, 2007), and the non-perceivable reduction in sucrose was conservatively calculated for at least 80% of the sample population, for example, a maximum of 20% of the sample population would be able to distinguish a difference in flavour.

Study 3: population modelling

Population modelling was used to estimate the impact of the extra energy as a result of caffeine in SSBs (compared with a non-caffeine scenario) on the total calories consumed at the population level, and the subsequent impact on population body weight. Using the weights and energy density values of beverages from the 1988–1994 and 1999–2004 NHANES studies (Wang *et al*., 2008; Bleich *et al*., 2009), estimates were made of a theoretical shift from caffeinated to non-caffeinated sugar-sweetened soft drink energy intake for children (aged 2–19 years) and adults (aged > 19 years) in the United States population. For both children and adults, the change in energy intake was expressed as a proportion of the average daily population energy intake. The expected impact on changes in mean population body weight was then estimated using validated coefficients (Swinburn *et al*., 2006, 2009, 2010). For both children and adults, the changes in mean population body weight were then expressed in terms of years of secular weight gain averted, using the average annual weight gain of these populations for the period 1970–2000 (US Census Bureau, 2008, 2009). Uncertainty estimates were included for each of the steps in the model, calculated using a Monte Carlo simulation with 5000 iterations (@RISK software, version 4.5, Palisade Corporation, Ithaca, NY, USA) to give an overall estimate (with 95% confidence limits) of the influence of caffeine in SSBs on weight gain.

Results

Study 1a: detection threshold determination of caffeine in water and sucrose

There were no significant differences in thresholds replicates for subjects and subject mean thresholds were used for analysis. There was a significant difference ($P < 0.001$) between the mean detection threshold for caffeine in water 1.09 ± 0.08 mM and caffeine in sucrose solution 0.49 ± 0.04 mM. There was large individual variation among subjects' caffeine thresholds with ranges from 0.33 to 2.65 mM caffeine in water and 0.08 to 1.57 mM caffeine in sucrose solution.

Study 1b: the effect of caffeine on sweetness

A directional comparison showed that 19 of 23 subjects chose sucrose alone (204 mM) as being sweeter than the mixture of sucrose solution and 0.67 mM caffeine ($P < 0.001$).

Study 2: caffeine–calorie effect: non-perceivable reduction in sugar from SSBs

When given identical solutions to assess, sucrose could be reduced by 9 mM (2.6% w/v) without > 80% of subjects identifying a change in flavour, and this was a consistent non-perceivable difference whether the solutions were caffeinated or non-caffeinated, SSBs or sucrose (Figures 2a and b; data for sucrose solutions not shown). However, when caffeinated versus the non-caffeinated solutions were tested, the non-perceivable reduction for sucrose in SSBs was 36 mM (10.3% w/v) without a perceivable difference in flavour for > 80% of the subjects (Figure 2c). This corresponds to a reduction of 116 kJ per 500 ml SSB serving without affecting flavour for > 80% of subjects.

Study 3: population modelling

For all United States adults (> 19 years), including non-SSBs consumers, mean SSBs consumption was estimated as 203 ml/day (Bleich *et al*., 2009), corresponding to 853 kJ/day. Based on industry reports (Datamonitor, 2007), 63.4% of this consumption was from caffeinated SSBs (541 kJ/day). From the study 2 results, if caffeine were to be removed from these SSBs their sucrose content could be reduced by 10.3% without affecting flavour. This would correspond to an energy reduction of 56 kJ/day for adults, assuming no compensatory increases in energy intake from other sources. The mean reduction in population body weight that would result from this decrease in energy intake is 0.60 (confidence interval 0.56, 0.63) kg (Swinburn *et al*., 2009). Given that the change in United States adult body weight between the early 1970s and the early 2000s (US Census Bureau, 2008, 2009) was 8.6 kg, or 286 g/year, this component has the potential to represent 2.08 years of secular weight gain for adults.

For children and adolescents (2–19 years), including non-SSBs consumers, mean SSBs consumption was estimated at 224 ml SSBs/day (Wang *et al*., 2008), corresponding to 941 or 596 kJ/day from caffeinated SSBs. This equates to an energy reduction of 61.4 kJ/day, assuming no compensatory energy intake from other sources. Based on a mean energy intake of 8556 kJ/day (USDA, 2008), this corresponds to 0.72% of total energy intake. Using an estimated mean population body weight of 44.5 kg (CDC, 2004) and the relationships between energy intake and body weight identified in Swinburn *et al*. (2006), the mean population body weight change that would result from this decrease in energy intake is 0.144 (confidence interval 0.120, 0.170) kg. This component of the caffeine–calorie effect has the potential to represent 1.1 years of secular weight gain for children, based on an annual change in weight of 133 g/year over 30 years (US Census Bureau, 2008, 2009).

Discussion

Removing caffeine from SSBs, allows for a 10.3% reduction of sucrose without a perceivable difference in flavour for > 80% of the subjects. Extrapolating these results using NHANES SSB consumption data, the excess energy in the SSBs due to caffeine is equivalent to 2.08 years of secular weight gain for adults and 1.1 years weight gain for children. This calculation did not take into account potential compensatory changes in diet in response to a proposed reduction in sugar, but there is no strong evidence to indicate what these effects might be (Rolls, 2009, 2010).

The classic epidemiological triad (hosts, vectors and environments) is a well-tested model for addressing a variety of epidemics including obesity (Egger *et al*., 2003). SSBs, a source of excess sugar consumption, is a classic example that fit the vectors rule of 'small changes × large volumes = significant population benefits'. There is good evidence for the contribution of high sugar products as an important determinant of obesity (Swinburn *et al*., 2004; Harrington, 2008) and good evidence that reducing them reduces weight (James and Kerr, 2005). This study suggests that the inclusion of caffeine in SSBs has had a small effect on unhealthy weight gain for the average individual but viewed in population terms, this may be one of many such influences driving the obesity epidemic and its contribution appears to be significant in terms of secular change. Although the removal of caffeine and subsequent co-removal of sugar energy may be a theoretical intervention for reducing population energy intake, it is unlikely to be a practical option given the undoubted enormous industry and consumer pressure to maintain the *status quo*. Nevertheless, the addition of caffeine to new products, including those high in sugar and fat, should be avoided to prevent a further increase in the amount of energy consumed in the population.

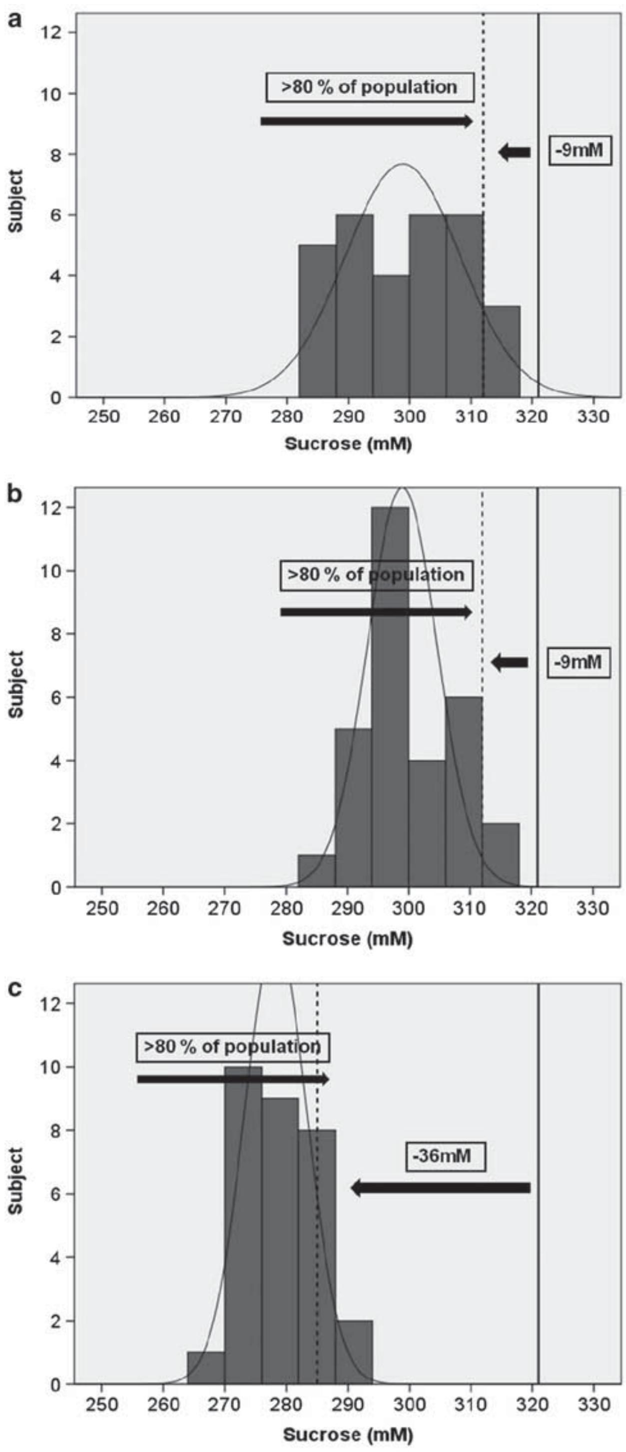

Figure 2 (**a–c**) The potential sucrose reduction in A/ non-caffeinated SSBs, B/ caffeinated SSBs, C/ SSBs with caffeine removed as determined by paired comparison test. The *y* axis represents number of subjects and the *x* axis represents sucrose concentrations. The solid black vertical line represents 321 mM sucrose concentration to which the variable sucrose concentrations were matched using directional paired comparison tests. The vertical dashed line splits the sample population 80:20, where at least 80% of population could not detect a difference in flavour between the two solutions. The mM concentration is the amount of sucrose that can be reduced without at least 80% of the population detecting a difference in flavour.

Further to this, it is a somewhat alarming trend that an increasing number of non-traditional high-energy caffeine sources such as candies, ice creams, breakfast cereals, yogurt and chewing gums are entering the food supply (Temple, 2009). Results from this study indicate that caffeine in SSBs may encourage unhealthy weight gain by passive over-consumption of energy and therefore there is a need for tight regulation of caffeine as a food additive, particularly because of the uncertain but likely greater impacts of caffeine in children (Temple, 2009).

Some limitations of this study warrant discussion. Although the results are conclusive for the SSBs and sweetener in this study, they may not be applicable to all foods, as food matrices and interactions between other chemicals may confound results. Another potential limitation of this study is our assumption that there would be no compensatory changes in energy intake (from other sources) in response to the decreased sucrose intake from SSBs. There is some evidence to suggest that, for children, changes in overall energy intake are likely to be greater than the reduction in energy intake resulting from decreased SSB intake alone (Striegel-Moore *et al*., 2006; Wang *et al*., 2009). In this case, our assumption is likely to be conservative.

For adults, the evidence is mixed, with some studies (DiMeglio and Mattes, 2000) showing that overall energy intake is likely to decrease by more than the energy reduction from SSB, whereas other studies (Reid *et al*., 2007) report opposite results. It is also noted that the results of the population modelling are highly sensitive to the equations used for estimating the relationship between changes in energy intake and body weight. The slope of the equation used for adults closely matches the slope estimated in other models (Swinburn *et al*., 2010), but the quantification of this relationship needs further validation. Although all subjects were regular caffeine consumers, we did not assess their daily consumption of caffeine, and potentially habitual high level caffeine consumers could become tolerant to caffeine's effects on sucrose perception or maybe even more sensitive. The results for non-perceivable difference in flavour are not applicable to 100% of the population due to the large individual variation in sensitivity to chemicals such as caffeine (Bartoshuk, 2000), they are, however, applicable to >80% of the sample population.

Conclusion

It is likely that the caffeine in SSBs is a contributor to the growing obesity epidemic, given the volume of current SSB consumption. The addition of caffeine should not be permitted to other foods and beverages without this serious consequence being included in the decision.

Conflict of interest

The authors declare no conflicts of interest.

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Author contributions

Our responsibilities were as follows: RK, LR and BS conceived the study and helped conceptualize ideas, interpret findings and reviewed drafts of the manuscripts. DS was involved in data collection, interpretation of findings and reviewed drafts of manuscripts. GS and BS were involved with population modelling and reviewed drafts of the manuscripts. RK led the writing.

Trial registration: Australia and New Zealand Clinical Trial Registry 2608000151336.

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