Simulations of the effects of scheduled abdominal aortic aneurysm repair on survival

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Summary

I simulated survival with and without scheduled repair of abdominal aortic aneurysms with different diameters in different populations. The results imply that scheduled repair should be determined by the combination of a patient’s monthly mortality hazard and aneurysm diameter. The median survival of some patients will be extended by the scheduled repair of aneurysms smaller than 55 mm, whereas the median survival of other patients will be curtailed by repair of any aneurysm. The results also suggest that, on average, surveillance is futile: the effect of scheduled aneurysm repair on an individual’s median survival did not change but the cohort effect diminished as patients died during surveillance. The results of the UK Small Aneurysm Study were reproduced in simulation and are compatible with the repair of aneurysms smaller than 55 mm diameter. Epidemiological simulations suggest that past randomised controlled trials underestimate the effect of aneurysm repair today.

Introduction

This paper simulates survival in patients with abdominal aortic aneurysms. The simulations address the following questions:

- ‘How might a patient’s general risk of dying – due to age, health and fitness – affect his/her survival trajectories with and without scheduled aneurysm repair?’
- ‘How might the aneurysm diameter affect survival trajectories with and without scheduled repair?’
- ‘How much does endovascular repair prolong survival compared with open repair?’
- ‘When is the optimum time and what is the optimum aneurysm diameter to schedule repair and how are they affected by a patient’s general risk of dying?’
- ‘How applicable today are the results of randomised controlled trials of scheduled aneurysm repair conducted 20 years ago?’
- ‘How might we quantify the net effect of scheduled aneurysm repair on survival – can we reasonably expect to distinguish between those whose lives would be shortened by surgery and those whose lives would be extended?’

Although ruptured aneurysms can kill, scheduled aneurysm repair can also kill. Patients with aneurysms can die from a myocardial infarction, pneumonia, colon cancer, a road traffic accident and by many mechanisms other than aneurysm rupture. A patient might reasonably anticipate that they would be counselled on the net survival effect of scheduled abdominal aortic aneurysm repair, as an individual, not as an
elusive ‘average’ patient. Earlier repair of some aneurysms less than 55 mm diameter compared with later repair of some aneurysms, often less than 55 mm diameter, 22 years ago [1], had little effect on median survival, which has resulted in the crude conclusion that surgeons should avoid repair on male aneurysms less than 55 mm diameter. An even cruder conclusion is that in males, surgeons should repair aneurysms 55 mm diameter or larger, made in the absence of randomised controlled trials, supported by the weak logic that larger aneurysms are more likely to rupture and kill. The conclusion that a diameter of 55 mm divides injudicious surgery from injudicious surveillance ignores the massive variation in patients’ life expectancies, their probabilities of dying before an aneurysm ruptures and their probabilities of dying as a result of having surgery.

The indiscriminate institution of a 55 mm aneurysm diameter to define acceptable clinical practice is contrasted by the widespread rejection of the ineffectiveness of endovascular repair in ‘unfit’ patients with aneurysms of a mean (SD) diameter of 68 (10) mm [2], again 20 years ago. The transient relative safety of endovascular compared with open repair [3], coupled with ‘advances in technology’, might explain the futile practice of operating on patients unlikely to benefit. Survival at one postoperative month as a measure of success typifies a thoughtless approach to the wisdom of surgery.

For the past 6 years, I and my colleagues have attempted to estimate and graph survival trajectories with and without scheduled abdominal aortic aneurysm repair for individual patients. Patients consider the estimated net effect of surgery, as well as their reduced survival probability immediately after surgery and their later increased survival probability. Patients with higher monthly mortality hazards have higher postoperative mortalities, less life to gain and a greater proportion of life to loose from scheduled aneurysm repair. Patients with otherwise long life expectancies may benefit from scheduled repair of aneurysms smaller than 55 mm diameter, whereas patients with short life expectancies will not benefit from repair of a large aneurysm even if rupture of the aneurysm is the most likely cause of death. For some patients, scheduled surgery will not increase survival and may result in a net reduction in survival. When I see such a patient who presents to our pre-operative assessment clinic after screening, I wonder whether they might have been better counselled before participating in the screening programme.

Patients should be the arbiters of their own fate and it is with them in mind that I have developed a survival calculator. This paper uses the calculator validated in the companion paper of postoperative survival in nearly 1000 patients after scheduled repair of abdominal aortic aneurysms [4].

Methods

I generated three survival curves for individuals or cohorts with abdominal aortic aneurysm: one without surgical repair; one after scheduled open repair; and one after scheduled endovascular repair. The survival curve with surgery accommodated the mortality hazard associated with surgery. The survival curve without surgery accommodated the mortality hazard of rupture from an expanding aneurysm. Both curves are based upon a common underlying survival curve to which the hazards of surgery or aneurysmal rupture are added. The common underlying survival curve starts with a monthly mortality hazard. In an accompanying paper, I have described in detail how variables are entered into a calculator to generate a monthly mortality hazard and subsequent survival curve for an individual without an abdominal aortic aneurysm [4]. In summary, the calculator uses: year; sex; age; height; weight; blood creatinine concentration and estimated glomerular filtration rate; myocardial infarction; stroke; peripheral arterial disease; angina; transient cerebral ischaemia; peak oxygen consumption and ventilatory equivalent for carbon dioxide (at the anaerobic threshold), both from a cardiopulmonary exercise test. I also described how the temporary increase in mortality resulting from scheduled open and endovascular aneurysm repair is incorporated into the calculation.

For the simulations in this paper, I entered values into the calculator that generated initial monthly mortality hazards of 0.5–2%. I chose these mortality hazards to illustrate problems faced by patients likely to present for ultrasound screening and scheduled repair of abdominal aortic aneurysm. Many different combinations of different values can result in the same
mortality hazard. The calculator uses the monthly mortality hazard to then generate a survival curve, which I have assumed was insensitive to the particular combination of values that generated the initial mortality hazard. For instance, a monthly mortality of 0.5% can be generated by the combination: the year 2000, male, 76 years old, 76 kg, 175 cm, no cardiovascular event (as detailed above), creatinine 113 μmol.l⁻¹, peak oxygen consumption 1431 ml.min⁻¹, ventilatory equivalent 30. The same monthly mortality can be generated by: the year 1996, female, 72 years old, 65 kg, 171 cm, myocardial infarct, creatinine 82 μmol.l⁻¹, peak oxygen consumption 950 ml.min⁻¹, ventilatory equivalent 36. The calculator would predict the same survival trajectory for these two patients.

I simplified the temporary increase in the mortality hazard caused by surgery as lasting one postoperative month, after which survival paralleled the pre-operative common underlying survival curve. I assumed that in the first postoperative month, the mortality rate increased compared with the pre-operative rate; ten times after open repair and four times after endovascular repair [1, 3]. I assumed the annual expansion of aneurysm diameter [5] to be:

\[
(0.0014 \times \text{mm} \times \text{mm}) - (0.065 \times \text{mm}) + 0.15.
\]

I assumed the annual rate of fatal rupture to be:

\[
(0.0001 \times \text{mm} \times \text{mm}) - (0.0068 \times \text{mm}) + 0.1215,
\]

where ‘mm’ is the aneurysm diameter in millimetres at the beginning of the year. I calculated the difference in median survival with and without surgery.

**Results**

In simulations, the higher a patient’s mortality hazard, the larger the aneurysm had to be for scheduled surgery to prolong survival, with endovascular repair prolonging survival by 2–6 more months than open repair. Figure 1 illustrates simulated survival with and without surgery for aneurysms 45–85 mm diameter and patients with initial monthly mortalities of 1%, 1.3% or 2%. Scheduled aneurysm repair increases median survival most for patients with the lowest mortality and the largest aneurysms. The differential effect on median survival of endovascular compared with open repair was greatest for patients with the highest monthly mortalities.

Figure 2 illustrates the continuous relationship between the effect of scheduled repair on median life expectancy and aneurysm diameter, for patients with monthly mortality hazards of 0.5%, 1% or 2%. This graph shows that the survival of some patients would be increased by scheduled surgery on aneurysms smaller than 55 mm diameter. Table 1 presents survival in 1000 patients with aneurysms 45 mm diameter and initial monthly mortality hazards of 0.5%, 1% or 2%. Survival was simulated for three scenarios: no surgery; immediate open repair of 45 mm aneurysms; and open repair when aneurysms were 55 mm diameter, expected after 6 years’ surveillance. Immediate open aneurysm repair prolonged median survival by 3 years in patients with a monthly mortality hazard of 0.5%, but had no effect for patients with a hazard of 1% and decreased survival in patients with a 2% hazard. Delayed aneurysm repair at 55 mm did not alter the median survival in any cohort, i.e. if screening identified a 45 mm diameter aneurysm in a patient with a monthly mortality hazard of 0.5% he (or she) should be offered immediate surgery. Surgery at 55 mm would prolong individual median survival by the same amount, 3 years (see below), but the median survival of the cohort would not be extended by planned delay because 37% of the cohort would have died in the intervening 5 years, more than a third of them from aneurysm rupture.

Figure 3 shows the effect of surgery on the median survival of cohorts versus the effect of surgery on the median survival of individuals. There were six cohorts, three with an initial monthly mortality hazard of 1% and three with an initial monthly mortality hazard of 0.5% (similar to the hazard estimated for the cohort in the Multicentre Aneurysm Screening Study [6, 7]). Observation started with aneurysm diameters of 40 mm, 45 mm or 50 mm. Median survival was increased most by scheduled repair of aneurysms that were largest (50 mm diameter in this example) when observation began. Median survival was increased most for patients with the lowest initial monthly mortality hazard, 0.5% in this example. The effect of scheduled aneurysm repair on the median survival of total cohorts (black lines) decreased the longer surgery was delayed. However, the effect of scheduled repair on the median survival of surviving individuals (red lines)
Figure 1 Simulated survival curves for patients with initial monthly mortality hazards of a) 1%, b) 1.3% and c) 2%, following scheduled open (---) or endovascular (----) abdominal aortic aneurysm repair. Survival for these patients without surgery is illustrated for five different aneurysm diameters: 45 mm (--); 55 mm (--.--); 65 mm (--.--.--); 75 mm (--.--.--.--); and 85 mm (--.--.--.--.--). Surgery increases median survival most for patients with the lowest mortality hazards, but surgery shortens survival in patients with 2% initial mortality (c) when aneurysms were smaller than 60 mm (open repair) or 47 mm (endovascular repair). Open repair compared with endovascular repair shortens median survival by: (a) 3 months; (b) 5 months; (c) 6 months.
remained fairly constant: decreasing general survival, which would reduce the effect of surgery, was counter-balanced by increasing mortality associated with an expanding aneurysm.

I estimated monthly mortalities for cohorts at the start of the UK Small Aneurysm Trial (UK SAT) and the US Aneurysm Detection and Management (ADAM) trial as 1/249 (0.40%) and 1/317 (0.32%), respectively, for which the mean aneurysm diameter was 46 mm (ultrasound) and 47 mm (CT scan), respectively [8, 9]. These diameters are similar to the 45 mm aneurysm group simulated in Table 1, for which immediate repair extended median survival by 3 years compared with delayed repair at 55 mm in a cohort with an initial mortality hazard of 0.5%. So why did UK SAT and ADAM conclude that earlier surgery did not prolong survival? Table 2 simulates results for UK SAT as if all the ‘surgery group’ had immediate aneurysm repair and it took 5 years for aneurysm expansion to reach 55 mm in the surveillance group, at which point they all immediately had surgery. The results are similar to the group in Table 1 that had an initial aneurysm diameter of 45 mm and monthly mortality hazard of 0.5%, i.e. immediate surgery extended survival by 3 years compared with aneurysm surveillance with surgery at 55 mm. Table 2 also simulates how the implementation of the UK SAT resulted in less polarised cohorts, due to delayed and incomplete repair in the ‘surgery group’, coupled with repair of aneurysms smaller than 55 mm in the surveillance group. The simulated results in Table 2 almost exactly match the reported survival, both illustrated by Fig. 4 that also shows that the simulation generated the observed crossover in survival curves 2–3 years after recruitment. In contrast, the results of ADAM are incompletely explained by simulation (Fig. 5). Simulation replicated the overall trajectories of the ‘surgery’ and ‘surveillance’ ADAM cohorts. However, the simulated crossing of survival curves at 1.5 years – simulated and observed at 2.5 years in the UK SAT – was not observed in ADAM.

The magnitude and direction of the effect of surveillance and scheduled surgery on the survival of patients with abdominal aortic aneurysms depends upon their baseline mortality rate and the initial aneurysm diameter. General population mortality rates have fallen year on year for more than five decades. The results of a published trial, conducted in the past would, therefore, be wrong if applied unadjusted to the current population. I simulated the recruitment of the UK SAT cohort today, ‘UK SAT 2015’. The initial monthly mortalities of these new cohorts, 22 years later, would be half the original, i.e. 0.20% (Table 3). Median survival would be extended 4–5 years by early surgery if UK SAT were repeated today. I have replicated the results of seven other randomised, controlled
trials of abdominal aortic aneurysm repair, which can be accessed online (Appendix S1).

The pre-operative aneurysm diameters were recorded for the Torbay cohort of 302 patients whose postoperative survival has been reported [4]. The effects of surgery on survival could, therefore, be simulated for individuals: scheduled surgery increased the median survival of the cohort by a median of 5 years 4 months after open repair and 5 years 7 months after endovascular repair. However, surgery increased survival by more than 18 years in the subgroup in the lowest mortality

### Table 1

Simulated survival over 11 years in cohorts of 1000 patients with initial monthly mortality rates of: (a) 0.5%, (b) 1% and (c) 2%. All patients had abdominal aortic aneurysms (AAAs) 45 mm diameter that: were not repaired; had immediate open repair; had open repair when 55 mm diameter, 6 years later. The boxes bracket the median life expectancies (500 survivors). Immediate open repair: (a) prolonged median survival; (b) did not affect median survival; (c) shortened median survival.

| Year | AAA diameter; mm | 0 | 45 | 46 | 48 | 50 | 51 | 53 | Subtotal | 0 | 6 | 7 | 8 | 9 | 10 | 11 |
|------|------------------|---|----|----|----|----|----|----|---------|---|----|----|----|----|----|----|
| a) No surgery | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| Deaths; year | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Deaths; year | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AAA deaths; year | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AAA deaths; year | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Open repair at 45 mm | 955 | 955 | 955 | 955 | 955 | 955 | 955 | 955 | 955 | 955 | 955 | 955 | 955 | 955 | 955 |
| Deaths; year | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Deaths; year | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AAA deaths; year | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AAA deaths; year | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

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hazard decile, but decreased survival in the subgroup in the highest mortality hazard decile (Fig. 6). Figure 7 illustrates the simulated relationship between monthly mortality hazard, aneurysm diameter and the extension of median survival with open (black) or endovascular (red) repair by (from top to bottom) 1 year, 2 years, 4 years or 6 years. Scheduled aneurysm repair would be indicated for combinations of mortality hazard and aneurysm diameter that intersected below whichever line is chosen as the minimum worthwhile increase in survival, whereas scheduled repair would be contraindicated for intersections above the line of indication. Median survival might be extended by 4–6 years following scheduled repair of 30 mm diameter aneurysms in patients with particularly low monthly mortality hazards. The $r^2$ value for each polynomial trend line exceeds 0.995.

Discussion
The simulations in this paper suggest a number of conclusions.

1. It is a patient’s characteristics, not aneurysm diameter, that predominantly determine the benefit or harm caused by scheduled aneurysm repair.

2. Scheduled repair of abdominal aortic aneurysms as small as 40 mm diameter can prolong survival in some patients, therefore a threshold of 55 mm for intervention will fail to prevent avoidable deaths.

3. Scheduled repair of abdominal aortic aneurysms larger than 55 mm, or 65 mm, or 75 mm, can shorten survival in some patients, therefore an intervention threshold of 55 mm will cause avoidable deaths.

4. Surveillance is predominantly futile – the absolute increase in median survival caused (in appropriate patients) by scheduled aneurysm repair is not increased by waiting: the increased probability of a larger aneurysm’s rupturing is counterbalanced by the patient’s diminished survival from other causes. In addition, the absolute benefit that might be realised from operating on a cohort early is partly lost by waiting (see point 2).
Table 2 Simulated survival for the UK Small Aneurysm Trial (UK SAT) participants: (a) as the study was conducted (see Fig. 4); (b) as if participants allocated 'surgery' had open repair immediately and participants allocated 'surveillance' had open repair after abdominal aortic aneurysms (AAAs) had expanded to 55 mm. The median survival for surgery triggered by aneurysm expansion to 55 mm was 7–8 years, which was prolonged to 10–11 years by immediate repair at 46 mm (b). The difference in median survival of 3 years was reduced to about 1 year in UK SAT because of premature surgery in the 'surveillance' cohort (median survival 8–9 years) and incomplete and delayed repair in the 'surgery' cohort (median survival 9–10 years). The initial monthly mortality was 0.40%. All the numbers are simulated, except for group sizes, the initial aneurysm size, and 'Reported survival'. The boxes bracket the median life expectancies in the 'Earlier surgery' cohort (282 survivors) and the 'Later surgery' cohort (264 survivors).

| Year | AAA diameter; mm | 0    | 1    | 2    | 3    | 4    | 5    | Subtotal | 6    | 7    | 8    | 9    | 10   | 11   | 12   | Subtotal | Total |
|------|------------------|------|------|------|------|------|------|----------|------|------|------|------|------|------|------|----------|-------|
| a)   | Earlier surgery (n = 563) |      |      |      |      |      |      |          |      |      |      |      |      |      |      |          |       |
|      | No surgery       | 563  | 529  | 488  | 444  | 398  | 351  | 303      | 254  | 206  | 160  | 117  | 82   | 76   | 55   | 57       | 59    | 62   | 65   | 68   | 72   | 76   | Subtotal | Total |
|      | Deaths; year⁻¹  | 0    | 34   | 41   | 44   | 46   | 47   | 48       | 49   | 48   | 46   | 43   | 38   | 31   | 303  | 505      |       |      |      |      |      |      |        |        |
|      | Deaths; year⁻¹%  | 0    | 6    | 8    | 9    | 10   | 12   | 14       | 16   | 19   | 22   | 27   | 32   | 39   | 303  | 505      |       |      |      |      |      |      |        |        |
|      | Scheduled repairs; year⁻¹ | 248  | 242  | 11   | 8    | 2    | 2    | 1        | 1    | 0    | 0    | 0    | 0    | 0    | 55   | 55       |       |      |      |      |      |      |        |        |
|      | Survival by treatment | 553  | 512  | 485  | 457  | 429  | 403  | 377      | 351  | 325  | 300  | 275  | 251  | 228  | 251  | 228      |       |      |      |      |      |      |        |        |
|      | Reported survival | 488  | 428  |      |      |      |      | 375      | 318  | 255  |      |      |      |      | 118*  | 118*      |       |      |      |      |      |      |        |        |
|      | Deaths; year⁻¹  | 10   | 41   | 27   | 28   | 28   | 26   | 26       | 26   | 25   | 25   | 24   | 23   | 175  | 175  | 335      |       |      |      |      |      |      |        |        |
|      | Deaths; year⁻¹%  | 2    | 7    | 5    | 6    | 6    | 6    | 6        | 7    | 7    | 8    | 8    | 8    | 9    | 9     | 9        |       |      |      |      |      |      |        |        |
|      | Deaths delayed; year⁻¹ | –10  | –7   | 14   | 16   | 18   | 21   | 22       | 22   | 21   | 21   | 18   | 14   | 8    | 12   | 170      |       |      |      |      |      |      |        |        |
| b)   | Later surgery (n = 527) |      |      |      |      |      |      |          |      |      |      |      |      |      |      |          |       |      |      |      |      |      |        |        |
|      | No surgery       | 527  | 495  | 456  | 415  | 373  | 328  | 283      | 238  | 193  | 150  | 110  | 74   | 44   | 44    | 44       |       |      |      |      |      |      |        |        |
|      | Deaths; year⁻¹  | 0    | 32   | 39   | 41   | 42   | 45   | 45       | 45   | 45   | 43   | 40   | 36   | 30   | 284  | 483      |       |      |      |      |      |      |        |        |
|      | Deaths; year⁻¹%  | 0    | 6    | 8    | 9    | 10   | 12   | 14       | 16   | 19   | 22   | 27   | 33   | 41   | 41    | 41       |       |      |      |      |      |      |        |        |
|      | Scheduled repairs; year⁻¹ | 96   | 88   | 61   | 36   | 25   | 14   | 6        | 1    | 0    | 0    | 0    | 0    | 0    | 9     | 9        |       |      |      |      |      |      |        |        |
|      | Survival by treatment | 523  | 490  | 455  | 421  | 389  | 357  | 330      | 298  | 266  | 237  | 209  | 184  | 160  | 160   | 160      |       |      |      |      |      |      |        |        |
|      | Reported survival | 466  | 393  |      |      |      |      | 329      | 261  | 215  |      |      |      |      | 69*    | 69*      |       |      |      |      |      |      |        |        |
|      | Deaths; year⁻¹  | 4    | 33   | 45   | 34   | 32   | 32   | 27       | 32   | 29   | 28   | 25   | 24   | 197  | 197   | 377      |       |      |      |      |      |      |        |        |
|      | Deaths; year⁻¹%  | 1    | 6    | 9    | 7    | 8    | 8    | 8        | 10   | 11   | 12   | 12   | 13   | 13   | 13     | 13       |       |      |      |      |      |      |        |        |
|      | Deaths delayed; year⁻¹ | –4   | –1   | –6   | 7    | 10   | 13   | 18       | 13   | 13   | 14   | 12   | 11   | 6    | 87    | 106      |       |      |      |      |      |      |        |        |

*Incomplete follow-up at 12 years: less than 12 years had elapsed since recruitment for half of each cohort.
5 The results of the UK Small Aneurysm Trial and, to a lesser extent, the US Aneurysm Detection and Management trial can be reproduced in simulation. Simulation suggests that their results have been misinterpreted. Scheduled repair at 46 mm and 47 mm, respectively, would have prolonged median survival by about 3 years compared with repair at 55 mm. Repairs of aneurysms smaller than 55 mm in the surveillance group, coupled with incomplete and delayed repair in the early surgery group, reduced the power of both trials to detect a difference in survival.

6 The results, reported or simulated, of the UK SAT and US ADAM trial cannot be used today without adjustment. The UK SAT would have the power to determine a difference in median survival if it were conducted in exactly the same way today (2015), as early surgery would extend median survival by about 4.5 years, or by six years with 100% adherence to the protocol. Historical results become more inaccurate with time: the value of 4.5 years will underestimate the effect of early surgery in the future if the year-on-year reduction in general population mortality continues.

7 Endovascular repair extends median survival by 2–3 months for most patients, if one ignores the annual 1% fatalities due to rupture after endovascular repair, which might negate the small extension to survival afforded by EVAR. Survival is dominated by patients’ variables and whether an aneurysm is repaired or not; it is hardly affected by how the aneurysm is repaired.
Table 3 The UK Small Aneurysm Trial, median recruitment year 1993 (Table 2), updated to 2015 as the median recruitment year. (a) as the study was conducted; (b) as if participants allocated ‘surgery’ had open repair immediately and participants allocated ‘surveillance’ had open repair after abdominal aortic aneurysms (AAAs) had expanded to 55 mm. The initial monthly mortality for a cohort with the same age and co-morbidity has fallen during 22 years from 0.40% to 0.20%. The rates of aneurysm repair reported for UK SAT would result in a median survival of 11–12 years in the surveillance group and 16 years in the ‘surgery’ group (the table has not been extended to 16 years). Immediate repair would extend median survival to 18–19 years, whereas repair at 55 mm would increase the median survival by 1 year from that calculated with the rates of repair in the surveillance cohort. The boxes bracket the median life expectancies in the ‘Earlier surgery’ cohort (282 survivors) and the ‘Later surgery’ cohort (264 survivors).

| Year | AAA diameter; mm | Subtotal | Total |
|------|------------------|----------|-------|
|      | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Subtotal | Total |
| 0   | 46 | 48 | 49 | 51 | 53 | 55 | 360 | 314 | 265 | 215 | 164 | 116 | 73 |
| 1   | 23 | 30 | 32 | 36 | 39 | 160 | 43 | 46 | 49 | 50 | 51 | 48 | 43 | 330 | 490 |
| 2   | 30 | 32 | 36 | 39 | 160 | 43 | 46 | 49 | 50 | 51 | 48 | 43 | 330 | 490 |
| 3   | 32 | 36 | 39 | 160 | 43 | 46 | 49 | 50 | 51 | 48 | 43 | 330 | 490 |
| 4   | 36 | 39 | 160 | 43 | 46 | 49 | 50 | 51 | 48 | 43 | 330 | 490 |
| 5   | 39 | 160 | 43 | 46 | 49 | 50 | 51 | 48 | 43 | 330 | 490 |
| 6   | 160 | 43 | 46 | 49 | 50 | 51 | 48 | 43 | 330 | 490 |
| 7   | 43 | 46 | 49 | 50 | 51 | 48 | 43 | 330 | 490 |
| 8   | 46 | 49 | 50 | 51 | 48 | 43 | 330 | 490 |
| 9   | 49 | 50 | 51 | 48 | 43 | 330 | 490 |
| 10  | 50 | 51 | 48 | 43 | 330 | 490 |
| 11  | 51 | 48 | 43 | 330 | 490 |
| 12  | 48 | 43 | 330 | 490 |
|      | 314 | 265 | 215 | 164 | 116 | 73 |
| 13  | 164 | 116 | 73 |
| 14  | 116 | 73 |
|      | 265 | 215 | 164 | 116 | 73 |
| 15  | 215 | 164 | 116 | 73 |
| 16  | 164 | 116 | 73 |
| 17  | 116 | 73 |
|      | 314 | 265 | 215 | 164 | 116 | 73 |
| 18  | 265 | 215 | 164 | 116 | 73 |
| 19  | 215 | 164 | 116 | 73 |
| 20  | 164 | 116 | 73 |
| 21  | 116 | 73 |
|      | 314 | 265 | 215 | 164 | 116 | 73 |
| 22  | 265 | 215 | 164 | 116 | 73 |
| 23  | 215 | 164 | 116 | 73 |
| 24  | 164 | 116 | 73 |
| 25  | 116 | 73 |
| 26  | 73 |

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Screening should be based upon an individual’s calculated monthly mortality coupled with the probability that he/she has an aneurysm sufficiently large that treatment would prolong survival by a meaningful period. A more effective screening programme might be to identify and treat aneurysms 40 to 55 mm diameter in people with low mortality hazards, which would involve repairing many more abdominal aortic aneurysms than currently undertaken. The harm or benefit caused by screening is dependent upon treating the right people and also screening the right people, which cannot be determined by age and sex alone.

The discrimination and the calibration of the calculator that I used in these simulations have been tested against independent survival data in nearly 1000 patients [4]. Inaccuracies in simulated survival would be insufficient to discount the listed conclusions. The most likely inaccuracies in these simulations are the rates of aneurysm growth and aneurysm rupture: the epidemiology of both is heterogeneous [5]. Some of the heterogeneity might be explained by patients’ variables, which could only be determined with individual patient data from the studies that have reported these rates, so the uncertainty around the values of aneurysm growth and rupture are likely to remain as these data are probably unavailable. For instance, the rupture rate is higher in women for a given aneurysm diameter, so the simulations in this paper are more applicable to men than women. The inaccuracies introduced into the simulations explored in this paper are universal: they apply as much to the logic underlying current treatment and screening practices. The variation in the survival of individuals is dominated by known patient variables, rather than the unknown accuracy of estimated aneurysm growth and rupture rates. This paper uses those known variables, whereas current screening and treatment do not use known variables.

The results of these simulations challenge the basis on which abdominal aortic aneurysms are screened, observed and repaired. There are implications for patients, clinicians and those who commission and run screening programmes. The screening programme should reconsider how it selects an appropriate population, incorporating differences between people and also changes in the prevalence and behaviour of
I had anticipated that some patients might be too frail to benefit from the repair of any aneurysm but I had not anticipated that the repair of small aneurysms might be beneficial. I was surprised that waiting for an aneurysm to grow is unlikely to increase the absolute surgical effect on median life expectancy for an individual, although the relative change in survival would increase. For instance, surgery might increase median survival by 3 years for an individual now or in 5 years’ time (should they survive), but with a decreasing life expectancy 3 years represents an increasing proportion of survival available to an individual. This example stimulates a question, “What is the metric by which the value of aneurysm repair is gauged and is it the same for everyone?” Figure 7 could be used to determine whom to screen and it could help patients decide whether their aneurysms should be repaired. Not only does one have to consider the absolute and relative effect of surgery on survival, but one also has to consider the morbidity associated with operating or not operating, coupled with whether to continue or discontinue surveillance when surgery is contraindicated or declined.

Competing interests
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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Supplementary material.

Table S1. Data used to simulate six randomised controlled trials of scheduled abdominal aortic aneurysm repair: CAESAR; PIVOTAL; EVAR 2; OVER; EVAR 1; DREAM.

Figure S1. CAESAR simulation.

Figure S2. PIVOTAL simulation.

Figure S3. EVAR 2 simulation.

Figure S4. OVER simulation.

Figure S5. EVAR 1 simulation.

Figure S6. DREAM simulation.