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Influence of architectural layouts on noise levels in Danish emergency departments

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5	Influence of architectural layouts on noise levels in Danish emergency departments
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14

Abstract

15 This study aims to evaluate the effects of architectural layouts of emergency departments on activity 16 patterns/work routines and consequent noise levels. Three Danish hospitals' emergency departments 17 that had different layouts were investigated via on-site noise measurements over three days and 18observations of noisy activities. The time-averaged noise levels in the three emergency departments 19 turned out to be significantly different, ranging from 50 to 59 dBA. During the observation of noisy 20 activities, the noise levels and occurrences of individual activities were noted and correlated with the 21 long-term measurements. Major noise sources that have high correlations with the three-day noise 22 levels are identified as loud staff communication and noise from alarms/electronic devices. Potential 23 remedies are suggested in connection to the emergency departments' architectural layouts. Especially 24 unnecessarily loud communication between medical staff and loud and frequent equipment/patient 25 transportation noise need to be improved for more comfortable acoustic environments.

Keywords: Architectural layout, hospital emergency department, noise level, work patterns,
communication noise

28

30 **1. Introduction**

31 Florence Nightingale pointed out that all unnecessary noise in hospitals was harmful in the following 32 quote "Unnecessary noise is the most cruel absence of care which can be inflicted on either sick or 33 well," in her book "Notes on Nursing" published in 1859 [1]. The noise levels measured in hospitals 34 are, unanimously agreed by all, not satisfactory, for example, Refs. [2-7]. They largely violate the 35 current noise limit recommended by the World Health Organization (WHO), namely 35 dBA [8]. 36 From the previous noise measurements, it is clearly concluded that hospitals are unacceptably loud 37 and chaotic, with an increasing trend in the noise level from 1960 to 2005 [2]. Poor room acoustics 38 and loud noise negatively affect medical staff in terms of speech communication, job demands, 39 fatigue, stress, burn-out, and hearing loss [9,10]. Unpredictable loud noises can distract staff, interrupt 40 their performance, and increase medical dispensing errors particularly for complicated tasks [11,12]. 41 The negative effects of noise are also well documented in association with a parent's comfort, 42 recovery and sleep quality. [13,14,15] However, no previous work has discussed how much noise was 43 inevitable and how much was unnecessary, which is indeed a very challenging question to answer and 44 could also be highly case-dependent.

45 Dominating noise sources in hospitals are not only related to building operations but also to building 46 occupants, such as conversations, medical activities, transportation of medical equipment and patients 47 [16]. In an attempt to understand which noise sources could potentially be avoided and which range of 48 noise levels is realistically achievable with current state-of-the-art technologies, we aim to conduct 49 analyses of individual activities and work patterns in connection to the architectural design of 50 hospitals, thus gaining insight into which noise sources could be controlled without compromising the 51 quality of patient care. To the best of the authors' knowledge, only a few studies have correlated 52 objective acoustics parameters and architectural layouts in hospitals [16-18]. Particularly Ocku et al. 53 tried to link the floor layout designs to the reverberation times [18], but did not look into a correlation 54 with noise metrics.

In this study, we measured the noise levels in three hospital emergency departments (EDs) that had quite different architectural layouts. Via an observation study of the activities in the EDs, we aimed to

57 find out the noisy activities that contribute significantly to the total noise level and correlations 58 between the noise levels of individual activities and long-term noise measurements. The final 59 objective was to suggest useful guidelines to reduce unnecessary noise in the ED and to provide insights on good architectural designs. Unfortunately, we could not get a permission for room 60 61 acoustics measurements and collecting subjective perception from hospital staff and patients, so 62 instead we used the objective measures that have been proved to have a good correlation with staff 63 and patient's perception of soundscape in hospitals. The contributions of this study are three-folds: (1) 64 to categorize the loud noise activities in the ED and present their noise levels, (2) to correlate 65 individual sources' noise level with the long-term noise measurements, and (3) to suggest useful 66 design guidelines that help decrease the noise levels in relation to the architectural layout of the 67 emergency department.

68

69 2. Three emergency departments

70 An ED in Denmark normally consists of emergency treatment rooms (ER), a triage (TRI), and a bed 71 unit (BU). ER is a room for minor or less critical cases, where patients are typically examined, treated, 72 and usually sent home afterwards. According to a medical doctor Marie-Laure B. Jacobsson 73 (Sjællands universitetshospital, Køge), approximately four patients pass through here per hour on 74 average. TRI is a room for more serious problems and thorough examinations. Afterwards, patients 75 are either sent to another department of the hospital or receive proper treatments and are then sent 76 home. The average duration of the stay in TRI is six hours according to Dr. Jacobsson. BU is a room 77 for patients in need of intensive care and under observation. The patient stays in BU for a longer time. 78 In this study, only one sound level meter was permitted for noise measurements, which was located at 79 a safe location in the TRI areas in all three hospitals. Therefore, all measured noise levels only 80 represent the sound environment in the TRI.

81 2.1. Hospital A

Layout: In Hospital A, the three branches of the emergency department, namely ER, TRI, and BU, were physically separated. ER was separately located in an adjacent part of the building and BU was also fairly secluded and not shown in Fig. 1(a). Between these two sections, the reception was located

together with the staffs' main organizational workstation marked as "Office area" in Fig. 1(a). TRI
was located along the hallway with exits to the other parts of the hospital.

Noise consequences: It was noticed that TRI was the main section of loud activities, which spread noise widely. The entrance hall reserved for ambulance arrivals was noisy. At this central intersection, an alarm phone as well as a printer room were placed next to the office. A sound level meter was placed at this intersection, shown as a solid circle in Fig. 1(a). Patients were located in the ward along the TRI hallway and some areas in the hallway were used for bedridden patients as well. The lengths of the triage hallways were about 15 meters, enabling medical staff to communicate with raised voice from one end to the other.

94 2.2. Hospital B

95 Layout: Hospital B had the three main functions of the department separated as well. ER and BU 96 were located outside the main TRI room. At the time of this observational study and noise 97 measurement (April 2019), Hospital B just introduced this new triage, which was basically one big 98 room containing 12 beds and a centrally located office area, as shown in Fig. 1(b). The beds were 99 separated by protruding walls. If stricter privacy was needed, moveable room separators were 100 additionally used. A computer was located just next to each bed to minimize the need for back and 101 forth communication with the central office area.

Noise consequences: It was noticed that most activities could be heard by all individuals in the room as a consequence of one big open space. If one part of the room was noisy, such as coughing, noise coming from medical devices like respirators, the whole TRI became noisy. Moreover, the transportation setup contributed to increases in the noise level. Ambulance staff entered from the left door with patients and exited to the same door again. If patients were being transferred to another department, they left out of the right exit. Through this exit door, clean beds were transported to replace used ones. This created a lot of loud transportation noise, which affected everyone in TRI.

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114 Figure 1. Three emergency departments. (a) Hospital A, (b) Hospital B, (c) Hospital C. The sound

115 level meter location is indicated as a red solid circle and transportation paths are indicated with arrows.

116

(color online)

117 2.3. Hospital C

Layout: Hospital C had three branches of the emergency department widely spread as shown in Fig. 1(c). Through the official entrance, the waiting room was located, which was directly connected to the reception. The rest of the ward was a relatively open space, moderately separated by glass walls. ER was located at the left end with an exit to the rest of the hospital. The other end of the hallway, where the patients arrived by ambulances, was the TRI section, where more acute patients were treated. In between ER and TRI hallway, there were separate rooms, such as an office for medical staff and a printer room.

Noise consequences: The three main functions were well separated, ending up with less interactions and reduced noise. This excessively long distance of the hallway (42 meters) prohibited from a loud communication style, such as yelling. However, this long distance might affect other aspects of the staffs' daily work routine negatively.

129

130 **3. Observation study**

131 This observation study was intended to identify loud noisy activities and how frequently they occur, 132 and how loud such individual noise events could be. We installed a class-1 sound level meter (Fusion, 133 01 dB) at a secure place and monitored the sound pressure level real-time on the mobile phone via a 134 3G data modem. The sound level meter was located close to a reflecting surface in all three hospitals for consistency, and therefore the effects of sound reflection on the noise measurement were supposed 135 136 to be similar. The most important consideration in determining the measurement spot was security and 137 safety of the sound level meter, meaning that nobody accidentally touched or stopped it by any means. 138 Prioritizing the security of the sound level meter, the height of the sound level meter location varied 139 from 1.5 m to 2.5 m. For this observation study, the second author stayed close to the sound level 140 meter (about 1.5 m apart from the sound level meter) in TRI and observed loud and peculiar noise 141 sources. Once a noise event was noticed, its noise type, the starting and ending time were noted, and 142 later the corresponding equivalent noise level for each incident was calculated using logged sound 143 pressure levels. Note that the identified noise incidents lased for different time durations, and

144 therefore the time information was used to quantify the sound exposure together with the equivalent 145 noise level.

Previous research has used various noise metrics. It has been widely accepted to use the overall noise levels [16], i.e., noise levels containing all audible frequency contents from the 1/3 octave bands centered from 20 Hz to 20 kHz. The A-weighting network is the most suitable to approximate the frequency selectivity of the human auditory system, particularly for rather quiet sound around 40 dB [8]. Different indicators, such as equivalent, minimum, maximum, peak noise levels, have commonly been used in hospital noise measurements [8,19]. In this study, most noise levels are presented using the equivalent A-weighted noise levels. The observation in each TRI sections lasted about 3.5 hours.

153 3.1. Communication noise

Clear communication between staff is absolutely crucial, but the way it is conducted significantly 154 affects the sound environment. Particularly in the three EDs measured, we found significantly 155 156 different communication patterns. In general, many staff conversations were unnecessarily loud. In 157 Hospital A, conversations with raised voice across the rooms and hallway were found to increase the 158 noise level. In addition, personal conversations between staff increased the noise level. The noise 159 level distributions are shown in Fig. 2. In Hospital A, raised communication noise between staff along 160 the hallway was found to be the major problem, while in Hospital B the open structure of the TRI 161 made all communication loud everywhere. The A-weighted equivalent noise levels (LAcaT) over a time 162duration T is expressed as follows:

summarizes the equivalent noise level, the occurrence of noise events, and total duration of identified

172 noise events during the observation study in the hospitals.

According to the WHO community noise guideline [8], the signal-to-noise ratio (SNR) should be at least 15 dB when listening to complicated messages. In Sec.4, the background noise level in Hospital A, B, and C, from the long-term measurements were found to be 49.0, 53.5, and 44.5 dBA, respectively, and therefore the SNRs for the staff communication in Hospital A, B, and C ranged 13, 15, and 14 dB respectively. This concurred with the suggested 15 dB SNR in the WHO guideline surprisingly well [8].





180 Figure 2. Histogram of staff communication noise. (a) Hospital A, (b) Hospital B, (c) Hospital C.

(single column, color online)

Another important type of communication is communication between the staff and patients, of which the noise level, $L_{c,staff-patient}$, is largely affected by the communication style and acoustical factors, such as room acoustics and background noise. A similar noise trend to the staff communication was found in this type of communication in Fig. 3 and the resulting equivalent noise levels were 61.3, 69.1, and 59.9 dBA in Hospital A, B, and C, respectively. The noise level at Hospital C was the lowest, being 5 dBA and 9 dBA lower than Hospital A and B, respectively. In terms of the SEL, Hospital C was about 6 dBA and 7 dBA quieter than Hospital A and B, respectively.

Recko

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C. (single column, color online)

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193

194 *3.2. Transportation noise*

195 Medical activities are inevitable and must be prioritized, but transportation activities and non-medical

196 activities could be minimized or optimized. The main transportation noise was associated with bed

197 transportation with and without patients, but also related to food and test transportation.

¹⁹¹ Figure 3. Histogram of Staff-patient communication noise. (a) Hospital A, (b) Hospital B, (c) Hospital

In Fig. 4, the noise levels caused by transportation of patients, $L_{t,patient}$, are shown. Hospital A had many transportation incidents (*N*=24) with relatively long duration per incident (L_{Aeq} of 59.9 dBA). Hospital B did not have many incidents (*N*=13) yet with high noise levels due to its open space nature (L_{Aeq} of 67.6 dBA). Hospital C had a small number of transportation with low noise levels (L_{Aeq} of 59.1 dBA). In terms of sound exposure, the noise levels in Hospital A and B were 9 and 10 dBA higher than that in Hospital C.

204 Figure 4. Histogram of patient transportation noise. (a) Hospital A, (b) Hospital B, (c) Hospital C. 205 206 (single column, color online) 207 The patients arriving by ambulance are brought in by paramedics, who did not spend as much time as 208 the hospital staff. During the observations, it was evident that a lot of the transportation related to 209 ambulance arrival or departure were quite noisy mainly because of the paramedics. Therefore, the 210 paramedics should make efforts to bring down the noise caused by them. This was particularly pronounced in Hospital A and B, whereas the problem was less significant in Hospital C, partly 211 212 because the ambulance staff entered via a secluded entrance. The location of the central entrance for

213 bedridden patients arriving by ambulance led to more frequent noise in Hospital A than Hospital B,

where the patients arrived and left at different exits according to their symptoms and mostly remained

215 in their respective sections. This makes the noise exposure in Hospital C about 10 dBA lower than 216 those in Hospital A and B. 217 On the other hand, the transportation noise, which did not involve patients, $L_{t,non-patient}$ is shown in Fig. 218 5. Hospital C had the most incidents of transportation without patients, which might be attributed to 219 the longest hallway as shown in Fig. 1(c). Especially the noise of trolleys was noticeable in this 220 category, although most of them were quieter than the incidents observed in Hospital B in this

- 221 category. In terms of sound exposure, the noise levels in Hospital A was the lowest, being about 8 and
- 222 7 dBA lower than those in Hospital B and C, respectively.

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Figure 5. Histogram of non-patient transportation noise. (a) Hospital A, (b) Hospital B, (c) Hospital C.
(single column, color online)

227 3.3. Noise from electronic devices and alarms

228 Another noise category is sound events caused by alarms and electronic devices, e.g., phone rings and 229 printers. There have been a series of studies that claimed that hospital alarms and electronic devices 230 were unnecessarily loud, for example, Ref. [22]. In Fig. 6, the noise distribution of electronic devices 231 and alarms is shown. Hospital B had a lot of phone ringing and Hospital C had quite some noise 232 incidents of printer working noise near the reception, which could have been moved to another place to reduce the noise impact. Hospital C had the centrally located reception, where many conversations 233 234 and phone calls were audible, but with relatively low noise levels. Hospital A and C had equivalent noise levels of 60.9 and 59.5 dBA, while the equivalent noise level in Hospital B was 66.8 dBA. In 235 terms of sound exposure, the noise level in Hospital B was 13 dBA higher than that in Hospital A and 236 14 dBA higher than in Hospital C. 237





Figure 6. Histogram of electronics and alarm noise. (a) Hospital A, (b) Hospital B, (c) Hospital C.

(single column, color online)

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243 *3.4. Noise from non-medical activities*

The non-medical activity noise includes noise from door slamming, item dropping, and footsteps, some of which are related to highly stressful situations during critical medical activities. This type of noise is regarded to occur randomly and irregularly, but in Hospital B, about 30% of the incidents was related to rustling of room separators. Hospital A was quietest (58.9 dBA), while Hospital B and C had noise levels 6 and 1 dBA higher than that in Hospital A, respectively, in terms of sound exposure.

249 Figure 7. Histogram of non-medical activity noise. (a) Hospital A, (b) Hospital B, (c) Hospital C. 250 251 (single column, color online) 252 253

- Table 1. Summary of the equivalent noise level (LAeqT) in dBA, number of noise incidents (N), and
- total duration of noise incidents in second (T) for the noise sources identified in the hospitals.

272 level by 9 dB is equivalent to an increases of the number of events by a factor of 7.9. Therefore, the 273 noise level increase of 9 dB cannot be explained solely by the number of the visitors during the noise 274 measurement, which supports our hypothesis that work routines and the architectural layout in the ED 275 affect the sound environment. It is also evident in Fig. 8 that the background noise level during the 276 measurement was quite different in the hospitals measured.



277

Figure 8. Measured noise levels over 66 hours in three hospitals. (single column, color online)

279

280 In Fig. 9, the occurrence rate, OR(N), which is defined as the fraction of time that a level exceeds N 281 decibels [16], is shown using the A-weighted equivalent noise level and C-weighted peak level. From 282 Fig. 9(a) using the A-weighted equivalent level, we could estimate the background noise level based on the concept of L_{90} , the percentile noise level exceeded for 90% of the time of the measurement 283 duration [24]. In the hospital context, this background noise level is likely to represent the noise level 284 with no or quiet medical treatment and staff's communication. In Fig. 9(a), L_{90} was found in each 285 286 hospital by drawing a horizontal line from the OR value of 90%, ending up with quite different background levels of 49.0, 53.5, and 44.5 dBA in Hospital A, B, and C, respectively. It is already 287 288 clear that even the background noise alone cannot fulfil the stringent WHO guideline of 35 dBA [8].

289 OR(N) using the peak levels, $OR(N)_{peak}$, has been used in several recent studies, concluding that 290 OR(90)_{peak} was strongly related to subjective perception of staff [19] and OR(75)_{peak} to the patient 291 satisfaction [20]. Shibi et. al. also concluded that the $OR(100)_{\text{beak}}$ was strongly correlated with the 292 staff perception of noise-related health effects, such as distraction, stress, fatigue, and tension 293 headaches [21]. In this study, we could not collect subjective evaluations from staff and patients, and instead used $OR(N)_{peak}$ in Fig. 9(b) to evaluate the staff and patients' perception of the hospital noise. 294 295 From Fig. 9(b), OR(75)_{peak} values were 14%, 42%, and 7% in Hospital A, B, and C, respectively. 296 Therefore, it is likely that the patient satisfaction varied significantly based on the conclusion in Ref. 297 [20]. However, OR(90)_{peak} values are similarly small as 0.49 %, 0.64 %, 0.62%, respectively, and therefore the staff could not experience huge differences. Again, OR(100)_{peak} values are all below 298 299 0.001%, so it is unlikely to impact the staff's subjective perception. All in all, Hospital B seemed to 300 have the most demanding noise condition, particularly for patients.

Using the noise levels from the individual noise sources from Sec. 3, a correlation analysis [25] was made in Table 2. There are strong correlations between the total noise level, L_{total} , and the two noise sources, namely, staff communication and electronic and alarm noise ($L_{c,staff}$ and L_e). The transportation without patients has the weakest correlation with the 3-day-long noise levels in the three hospitals, indicating that it is unlikely to be seen as a major noise source, either having low noise levels or relatively low frequency of occurrence.



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Figure 9. Occurrence rate (OR) curves in the three hospitals. (a) L_{Aeq} and (b) L_{Cpeak} . (single column, color online)

Table 2. Pearson correlation coefficients among L_{total} , $L_{\text{c,staff-patient}}$, $L_{\text{t,patient}}$, $L_{\text{t,non-patient}}$, L_{e} , L_{act} , indicating the strength of the linear dependence between the pairs of variables. Correlation coefficients larger than 0.9 are indicated in bold.

316 **5. Discussions and suggestions to reduce noise level**

Hospital A: Patients' consultations in the triage hallway and the communication style between the staff led to a high noise level. Consultations were preferably moved to closed rooms for reducing noise as well as privacy purposes. Noise of alarm beeping and noise from the administrative office area were identified as problematic and partly unnecessary. Another subjectively found prominent noise source was the footwear of the staff members. Many wore flip-flops or clogs without heel straps causing slapping noise for every step. The doors of the wardrooms slammed occasionally, so soft close dampers would be recommendable.

324 Hospital B: There was a continuous noise from respirators over the majority of the observation time 325 and noise measurement, which significantly elevated the background noise in the ward. Phone 326 conversations were often overly loud. Additionally, the chairs for visitors placed at the bottom of each 327 bed could be moved to the head end of the bed, as people raised their voice due to the long distance 328 from the chair to the patient. The footstep noise was also loud here. It should be noted that the new 329 triage was introduced one day before the noise measurements and observation were conducted. As a 330 result, the staff was not accustomed to the new environment, which might have influenced the noise 331 level negatively, as they were still in an adaptation process.

Hospital C: The centrally-located reception could have been moved to a closed room to minimize the noise spread and to protect the patients' privacy. The waiting room could also be secluded from the rest of the ward. Electronic devices such as printers could have been moved to another closed or secluded location.

336

In general, we could suggest that ER needs be detached from TRI, or remotely situated and isolated as much as possible to minimize noise spread between ER and TRI. Small and separate patient rooms are preferred to avoid loud communication across rooms or hallways in terms of noise, but there are other reasons. A previous noise study in a Korean hospital highlighted that when the TRI was well separated from small ERs containing up to six beds after the outbreak of Middle East respiratory syndrome (MERS), a huge reduction of noise due to the change of the layout was reported by medical staff [7]. Therefore, such separated layouts are proven to be beneficial not only in terms of noise, but

344 also in terms of spread of contagious diseases. In addition to the separation of rooms, the doors can be 345 either sliding or softly closing to reduce the noise. Automatically closing doors can block the noise 346 transmission from one room to another effectively.

347 Separate entrances for specific purposes could help, as the noise emanating from the patients' arrival 348 by ambulance is quite loud. Having more equipment available near the patients could be beneficial to 349 avoid moving it back and forth through the ward. Electronic devices like printers should be re-located 350 in separate rooms preferably with closed doors.

351 Admittedly, this study has some weaknesses. One weakness of this study is a small sample size only 352 including three hospitals in Denmark. More data will certainly lead to clearer conclusions on the 353 major noise sources and their contributions to the total noise levels in hospitals. Second, only one 354 sound level meter was used to capture the noise level around the TRI area, and more measurement 355 points are needed to fully capture the sound field in the emergency department. The observation study 356 was conducted only for about 3.5 hours, which might not be sufficiently long time to capture the 357 general work pattern in the hospital. Again, the microphone height was inconsistent, but it was hard to compromise the security of the device. The acoustic characteristics of the EDs have not been 358 359 considered, which could influence the sound levels up to 3-4 dB depending on the acoustical 360 treatments [26]. In hospitals, many walls and floors are acoustically hard to guarantee that appropriate 361 cleaning and disinfection procedures can be applied. Therefore, there might be no big influence of the 362 room acoustic treatments on the measured noise, but the EDs are different in size and degree of acoustic coupling to connected rooms. Finally, no subjective data were collected, such as staff 363 364 satisfaction, stress, distraction, and fatigues. It is obvious that more meaningful conclusions could be drawn with correlating the subjective and objective measures, for example, which noise sources and 365 activities affected the staff work significantly. 366

368 6. Conclusion

369 This study investigates the main noise sources and architectural layouts in three Danish hospitals' 370 emergency departments and reports the noise data measured. The noise levels were measured for about three days, which are found be correlated with the noise exposure to communication noise and 371 372 electronic / alarm noise in the hospital. Loud communication, un-optimized and unnecessarily loud patient transportation, unnecessary electronic devices and alarm noise were identified as the noise 373 sources to be controlled. The largest difference among the A-weighted equivalent noise levels over 66 374 hours measured in three EDs was 9 dBA, which cannot be explained solely by the increased number 375 of patients. To improve the noise condition in the emergency department, it is recommended to avoid 376 a large open space not only for noise but also for preventing the spread of infectious disease, and not 377 to use a hallway of about 10-15 meters long as a ward, which makes the medical staff tempted to 378 379 communicate with raised voice in the hallway. Certain noise sources, such as unnecessary alarms / electronic devices and too loud footstep door slamming noise, must be minimized. 380

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Highlights

- Measurement of three Danish emergency departments over 66 hours
- Identification of noisy activities and presentation of their noise levels and durations
- Correlation between sound exposure to individual noise sources and longterm noise measurement
- Suggestion of useful design and operation guidelines to reduce the noise level in emergency departments in hospitals

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Declaration of interests

 \boxtimes The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

□The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: