SOUND EXPOSURE OF ST PAUL'S CATHEDRAL CHOISTERS

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1 INTRODUCTION

Choral singing is a very popular activity, and an estimated 37 million people regularly take part in collective singing in over a million choirs across Europe. This represents around 4.5% of the European population according to a survey, "Singing Europe" undertaken by the European Choral Association in 2015[1]. A 2017 survey of choral singing in the United Kingdom by Voices Now[2] estimated that 2.14 million people regularly sing in one or more of over 40,000 choirs. Choir members range in age from 6 years to over 100 years old and were from all backgrounds. For this research the focus was on St Paul's which is an Anglican church where the 'A Cappella' style of singing is at the fore. However, unusually no specific reference was made to this style in the survey[3].

Singing is considered noise under the Control of Noise at Work Regulations 2005[4]. These regulations are enforced by the Health and Safety Executive. There are two types of sound exposure: Peak levels measured using the acoustic parameter L_{Cpeak} and Average levels measured using the acoustic parameter L_{Aeq}, see Table 1. To give a normalised daily average a time period of 8 hour is used, this gives the acoustic parameter $L_{EP,d}$. If the $L_{Ep,d}$ was 85 dB then the noise dose, a linear value, would be 100%. Peak sound exposure limits were designed to capture explosive type sounds e.g. shooting and clashing. If the exposure was above the 137 dBC limit value then it is likely that immediate hearing damage would occur.

Average sound exposure limits were designed to measure over time sustained noise levels e.g. construction, mining or factory noise. These would cause a slow, but noticeable, decline in hearing acuity, called noise induced hearing loss. There is a small risk at 80 dBA as averaged over an hour 8 day over a 40 year working life of noise induced hearing loss, based on ISO 7029 and ISO 1999[5]. This risk increases at 85 dBA assuming the same work pattern, 8 hour day, 40 hours a week and a 48 week year.

Table 1: Noise exposure limits

	LAeq	**LCpeak**	**Noise Dose**
Lower Exposure Limit $L_{EP,d}$	80 dBA	135 dBC	50%
Upper Exposure Limit $L_{EP,d}$	85 dBA	137 dBC	100%
Weekly Exposure Limit $L_{EP,w}$	87 dBA	137 dBC	159%

2 SOUND XPOSURE MONITORING OF MUSIC

O'Brien *et al*[6] stated that due to the nature of orchestrated music noise exposure is difficult to measure. The associated hearing health problems in musicians have been extensively reported, for example Royster *et a7*[7]. However, not much known concerning noise-induced hearing loss in choir singers. Steurer *et al*[8] did find that professional choir singers did suffer from a permanent threshold shift compared to normative data[8] in the 125 Hz and 250 Hz frequencies. This matches the

fundamental vocal frequencies produced by trained singers as measured in men and women by Okten[9].

Choir singing noise exposure has been measured using a number of different methods that are compatible with the choral environment. Seaton[3] made recording using a cheap MP3 calibrated recording which was post-processed; Behar *et al*[10] undertook measurements of music teachers in schools using industrial dosimeters finding that the noise level limit, $L_{EP,d}$ was exceeded in 39% of classes. In Nigerian churches the sound level had been measured using Android sound level meter app based on the results in this NIOSH report[11]. It was found that for the 30 church services measured the Catholic congregation had an average $L_{EP,d}$ of 90.3 dBA, the Anglican services 83.4 dBA, and the Pentecostal a very high $L_{EP,d}$ of 95.4 dB[12]. It should be noted that the NIOSH report[11] recommended using iOS based apps and they would not be compliant with IEC 61252[13]. It is known that children, who are part of the congregation, could be more easily damaged by extremely high sound levels than adults[14].

For the noise measurement of the choristers it was decided to use standard dosimeters which meet IEC 60252: 1993[13]. The Audio[3] SoundBadge was found to be more compatible with children given the device's small size and lightweight dimensions[15]. Three dosimeters were used each was calibrated before and after each measurement using a sound calibrator meeting the requirements set out in IEC 60942: 1997[16]. In addition, calibrated Class 1 sound level meters meeting IEC 61672-1: 2014[17] were used to take survey measurements.

3 CHORISTER SOUND EXPOSURE MEASUREMENTS)

Four representative sound exposure measurements were undertaken over the course of five weeks during the Spring of 2019. Each measurement usually consisted of a rehearsal and performance and included multiple performers. Measurements were either taken using dosimeters worn on the shoulder, or sound level meters positioned at ear height behind the performer.

3.1 Performance 1: St John's – The Passion

Measurements were taken during the full performance of Bach's St John's the Passion. A 20-minute warm-up in the rehearsal room was measured for the choristers before the full 120 minute performance, which took place under the Dome of St Paul's Cathedral, see Table 2. The performance consisted of a large number of musicians including 26 choristers, an 80 member amateur choir, 18 professionals in the adult choir, and a ten-piece Baroque orchestra which considered of Strings/Woodwind, and a small organ.

Table 2: Choristers Sound Exposure: St John's – The Passion

	LAeq (dB)	**LCpeak (dB)**	**Duration (minutes)**
Warm Up	85.5	125.0	20
Performance Part I	84.1	114.5	38
Performance Part II	83.1	106.1	77

Hence, from Table 2, the warm up and performance gave an average level (L_{Aeq}) of 84.4 dBA over the 138-minute measurement. This is equivalent to an $L_{EP,d}$ of 78.4 dBA or 25% of the allowed noise dose. It can also be seen that all the peak levels were well below the allowed levels.

3.2 Performance 2: Quire Rehearsal and Performance (Chorister only)

Measurements were taken during a Quire rehearsal and Evensong performance. This was an unusual situation as the BBC wanted to film the performance and hence dosimeters could not be used. The choristers were positioned on the left side of the Quire on the lower two pews for the rehearsal and

performance for television, see Figure 1. Two sound level meters were located on the rear pew behind the boys at ear height for the rehearsal, see Table 3 and performance, Table 4.

Figure 1. Choristers all on one side of the Quire

Table 3: Quire Rehearsal Measurements

	LAeq (dB)	**LCpeak (dB)**	**Duration (minutes)**
Pew Left Rear	73.8	N/A	32
Pew Right Rear	75.5	121.1	32

Table 4: Quire Performance Measurements

	LAeq (dB)	**LCpeak (dB)**	**Duration (minutes)**
Pew Left Rear	70.9	N/A	44
Pew Right Rear	73.0	104.9	44

Combining the sound exposure levels for the rehearsal and performance, Tables 3 and 4, gave an average level, L_{Aeq} of 74.1 dBA (worst case). This is equivalent to a 2.0% noise dose. The peak noise levels, 121 dBC, were well below the peak noise limit of137 dBC.

3.3 Performance 3: Choristers + Adult Choir Rehearsal and Performance

Measurements were taken during a rehearsal and Evensong performance and consisted of 24 choristers and 12 adult members of the choir, see Figure 2. The adults (11 male, 1 female) joined the choristers half way through the rehearsal. Measurements were taken using four sound level meters positioned at ear height around the vaulted rehearsal room, see Table 5. In addition, three dosimeters were put on the adults: Choir Master, a male and a female member of the adult choir, see Table 6.

Figure 2. Choristers in their normal positions in the Quire

Table 5: Rehearsal Measurements (Choristers)

	LAeq (dB)	LCpeak (dB)	Duration (minutes)
Pew Left Rear	81.5	108.2	37
Pew Right Rear	82.2	109.0	37
Pew Left Front	86.3	112.8	37
Pew Right Front	85.9	111.6	37

Table 6: Rehearsal Measurements (Adults)

	LAeq (dB)	LCpeak (dB)	Duration (minutes)
Choir Master	84.9	114.0	37
Male Singer (Tenor)	87.0	117.0	19
Female Singer (Mezzo)	77.4	113.8	19

It can be seen from Table 5 that the front sound levels in the rehearsal room were higher than the rear. This is in line with the position of the male tenor, see Table 6. Hence, the main sound source was very likely to be the tenor. This agrees with the measurement of the Choir Master, 84.9 dBA, who stood at the centre of the rehearsal room. The adult female singer was significantly quieter, L_{Aeq} of 77.4 dB, she stood at the rear of the room. All the peak measurements were found to be well below the allowed limit value.

The rehearsal was immediately followed by Evensong hence the dosimeters were restarted and the sound level meters reset. The sound level meters were positioned at ear height behind the boys on the second and third row of pews, measurement shown in Table 7. The dosimeters were kept on the same people for the 40-minute performance, see Table 8.

Table 7: Measurements of the Evensong Performance in the Quire (Choristers)

	LAeq (dB)	LCpeak (dB)	Duration (minutes)
Pew Left Back	73.8	107.8	40
Pew Right Back	75.2	109.0	40
Pew Left Front	78.2	111.4	40
Pew Right Front	76.7	103.7	40

Table 8: Dosimetry Measurements of the Evensong Performance in the Quire (Adults)

	LAeq (dB)	LCpeak (dB)	Duration (minutes)
Choir Master	72.0	109.0	40
Male Singer (Tenor)	84.8	114.3	40
Female Singer (Mezzo)	77.8	112.7	40

Evensong produced noise levels that were lower than for the rehearsal, see Tables 6 and 8. However, the tenor was again the nosiest, 84.8 dBA, and the Choir Master was the quietest 72.0 dBA. The Choir Master was positioned substantially further away from the choristers and choir than in the much smaller rehearsal room. The chorister measurements were consistent at approximately 76± 2 dBA, see Table 7. All the peak measurements were found to be well below the limit value.

From the datasets it was possible to calculate the sound exposure of four different people: worst case chorister, Choir Master, tenor, and mezzo for the combined rehearsal and performance, see Table 9.

Table 9: Combined Rehearsal and Performance Noise Exposure

	LAeq (dB)	Noise Dose %
Choir Master	82.0	8.0%
Male Singer (Tenor)	85.6	14.1%
Female Singer (Mezzo)	77.7	2.3%
Chorister (Worst Case)	84.6	15.1%

The combined results, Table 9, show that all the performers were well within the allowed limits for noise dose. The tenor, although loud was only singing for a short duration, less than one hour, and hence only received a 14.1% noise dose. The worst case chorister, standing in front of the tenor, received a marginally higher noise dose 15.1 %, due to an additional 18 minutes of exposure.

3.4 Performance 4: Choristers + Adult Choir Rehearsal Quire Performance with Organ

Measurements were taken during a rehearsal, in the rehearsal room, and Evensong performance in the Quire. The performance consisted of 24 choristers, 12 adults in the choir and the organist. The adults (11 males, 1 female) joined the choristers half way through the rehearsal. Measurements were taken with two sound level meters positioned at ear height around the vaulted rehearsal room, see Table 10. In addition, two dosimeters were put on the tenor and the chorister who stood directly in front of the tenor, measurements are shown in Table 11.

Table 10: Measurements in the Rehearsal Room

	LAeq (dB)	LCpeak (dB)	Duration (minutes)
Rear Pew	87.9	120.7	40
Left Pew	90.4	119.5	40

Table 11: Dosimetry Measurements in the Rehearsal Room

	LAeq (dB)	LCpeak (dB)	Duration (minutes)
Male Singer (Tenor)	93.4	118.0	23
Worst Case Chorister	95.4	121.5	40

It can be seen from Table 10 that the sound levels were significantly higher than in previous rehearsals. The personal noise exposure levels on the chorister and tenor were higher still, see Table 11. This indicates that tenor was again the primary sound source in the room, with the chorister exposure even higher due to their relative positions in the pews. All the peak measurements were found to be well below the allowed limit value.

For Evensong the dosimeters were kept on the same people with the organist badged for the 59-minute performance, see Table 12.

Table 12: Dosimetry Measurements of the Evensong Performance with Organ

	LAeq (dB)	LCpeak (dB)	Duration (minutes)
Male Singer (Tenor)	95.1	119.5	59
Worst Case Chorister	95.1	N/A	59
Organist	79.7+91.0	102	59+5

Evensong produced noise levels that were similar to that measured during the rehearsal, see Tables 11 and 12. The tenor and the chorister standing directly in front of him were equally exposed, 95.1

dBA. The organist was relatively quiet during Evensong but then played the procession out of the cathedral which significantly increased his noise exposure.

From the datasets it was possible to calculate the noise exposure of the three performers: chorister (worst case), tenor, and organist, see Table 13.

Table 13: Combined Rehearsal and Performance Noise Exposure

	Averaged LAeq (dBA)	**Noise Dose %**
Adult Tenor	94.7	160.2%
Chorister	95.2	218.9%
Organist*	82.6	7.6%

*Organist played out the procession

When calculating the combined noise dose for the day for the three performers under investigation it can be seen from Table 13 that the daily limit was exceeded for the tenor (82-minute exposure) and the chorister (99-minute exposure) by a significant margin, 160% and 219% respectively. However, the organist was significantly below the 85 dBA daily limit and due to the short duration (64 minutes) and lower noise level, giving a noise dose of only 7.6%.

4. CALCULATION OF WEEKLY AND ANNUAL SOUND EXPOSURE

Working closely with the Music Department it was possible to estimate the weekly dose value for the Choir Master, worst case chorister, tenor, and organist based on the schedule, see Table 14. It should be noted that the long rehearsals had a duration are 70 minutes.

Table 14: Weekly Schedule for the Musicians

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
Choristers	Warm Up 2 Rehearsals	Warm Up 2 Rehearsals Evensong	Warm Up 2 Rehearsals Evensong	None	Warm Up 2 Rehearsals Evensong	Warm Up 2 Long Rehearsals Evensong	Warm Up 2 Rehearsals 3 Services
Adult Choir	No	Yes	Yes	Yes	Yes	Yes	Yes
Organist	No	Yes	Yes	No	No	Yes	Yes
Choir Master	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Taking the schedule and combining the representative measurements given in section 3 it is possible to create an estimation of the noise exposure of four performers see Table 15

Table 15: Daily Noise Exposure for Four Musicians

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
Chorister	4.7%	144.8%	144.8%	N/A	47.3%	135.4%	433.0%
Choir Master	4.7%	33.0%	33.0%	N/A	20.0%	37.0%	66.0%
Tenor	N/A	140.8%	140.8%	17.6%	6.5%	130.1%	431.0%
Organist	N/A	7.6%	7.6%	N/A	N/A	7.6%	22.8%

It can be clearly seen from Table 15 that the Tenor and Chorister (worst case in front of the Tenor) are the performers with the highest sound exposure. Usually the upper exposure limit, 85 dBA, is used to calculate the noise dose, which is normalised to 100%. There is also an absolute weekly exposure limit of 87 dBA which gives a 159% noise dose. It can be seen from Table 15 that this exposure limit noise dose is higher than the measured noise dose for every day except for Sunday.

When the Chorister weekly noise dose is estimated, the summed value is 829.0%. This is greater than the weekly allowance of 792.4%. However, when the school year is considered, a 37 week year, rather than the 48 week year considered as normal in the regulations, the adjusted apparent annual sound exposure is 639%.

For the Tenor the calculated weekly sound exposure was 789.9% which is lower than the allowed 792.4% exposure limit. Again, the Tenor does not sing all year, the adults singing for 42 weeks, and in fact a 77% attendance was recorded for the tenor in question in 2018 (average adult attendance was 69% that year). As such the apparent annual sound exposure is 476.9% just below the normal limit value of 500%.

5. CONCLUSIONS

A study was undertaken by the Acoustics Group, London South Bank University with the full collaboration with the Music Department of St Paul's Cathedral on the sound exposure of the Choristers, Choir, Music Director and Organist. Based on a representative sample of measurements of both rehearsals and performances the daily, weekly and yearly noise dose was calculated.

It was found that the Organist and the Music Director were well below the allowed dosage. However, the Chorister directly in front of the Tenor (worst case location) was above the daily and the weekly exposure limit. This was mitigated by the shorter working year of the children and hence the apparent exposure was within the allowed limit. Peak levels were found to be well under the exposure limit values for all performers for all rehearsals and performances measured.

6. Recommendations

St Paul's is compliant with the Control of Noise at Work Regulations but needs to be vigilant. The figures presented here represent a worst case scenario and the results of, for example, the full choir with organ service (which contained large-scale accompanied repertoire for the Installation of the Precentor) have been applied liberally to all services utilising these forces. It should be noted that many of the choral services are not on this scale, and that much of the regular repertoire is unaccompanied (even when the Organist is present) and 'smaller' in nature. Nonetheless, the recommendation is to consider managerial techniques that could be used to reduce the health risk to the Choristers.

In other contexts (e.g. an Opera Chorus) we would recommend that singers be rotated on a daily basis, particularly when the full choir is rehearsing / performing, as this would significantly reduce their sound exposure (the reduction in noise dose is difficult to calculate precisely, but could be of the order of 25%). We recognise that this could be difficult to do regularly in the context of the St Paul's set-up, but that reconfigurations are possible when, for example, older boys leave the choir because of voice change, something that occurs (albeit unpredictably) throughout the year.

The large number of rehearsals and performances on a Sunday result in a very high noise dose. Current proposals for a Girls' Choir to sing Evensong every Sunday afternoon would mean that over the course of a two-week period the boys' Sunday exposure would be reduced from 480% to 418%.

It can be observed that many of the highest measurements occur in the Rehearsal Room. The Cathedral may like to consider the introduction of wooden diffusers in that space. The diffusers would be attached to the ceiling but would not need to be classed as 'permanent' in the architectural sense (though permissions would still be required). This would result in a reduction of 3dBA at all rehearsals

equivalent to a further 80% reduction in Choristers' noise dose, giving a maximum dose of 338% over a typical week for the worst case chorister.

By combining these suggestions, the weekly noise exposure of the choristers would be below the weekly sound exposure limit. This would then be additional to the Cathedral's existing compliancy with the annual limit and would admirably demonstrate the willingness of the organisation to exercise a robust attitude towards Duty of Care in relation to Choristers.

7. REFERENCES

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