Real ear acoustical characteristics of impulse sound generated by golf drivers and the risk to hearing

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Real ear acoustical characteristics of impulse sound generated by golf drivers and the risk to hearing

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ARTICLE SUMMARY

Article focus

1. Is there a risk to hearing for amateur golfers when using the driver golf club?
2. If so, is this risk more prominent in one ear or equal across ears?
3. Does the speed of the swing influence the sound generated?

Key Messages

1. The results indicate varying levels of noise produced by clubs but negligible risk to hearing of amateur golfers, with a daily noise exposure of 2.5% when averaging the results of the loudest club.
2. No difference was found between ears.
3. Swing speed does not have a significant correlation to the sound generated.

Strengths

1. An innovative approach taken by using in-the-ear recordings that provide sound pressure levels at the tympanic membrane. This provides a more accurate estimation because it takes ear canal resonance properties into consideration, whereas the alternative of using a sound level meter equidistant does not provide this detail.
2. Using the recordings in-the-ear canal provides ear independent recordings.

Limitations

1. Three standard clubs as well as the participants own club meant that a small sample of golf clubs was used in the study.

ABSTRACT

Background/Aims

This study investigated the intensity and frequency responses generated from golf club drivers at impact with a golf ball. In situ recordings were made from the ear canals in order that ear specific information was obtained. The risk of hearing loss from these results was then calculated.

Methods

19 adult male participants struck 6 golf balls with each of the 4 golf drivers clubs. GN Otometric Freefit wireless Real Ear Measurement System (REM) was used to record the acoustical responses of the impulses sounds generated. A Swing Speed Radar® system was used to investigate the relationship between noise level and swing speed.

Results

One club generated significantly higher intensity levels of impulse noise than the others with a mean dBA recordings of 100.0 and 98.2 for the far and near ear respectively. There was no significant difference between the ears and a small positive correlation was found between noise intensity and swing speed.

Conclusions

If a basket of 40 balls are consistently hit at 116 dBA mean intensity, there is significant risk to hearing. When using the maximum recorded levels from the study with club 1 which was 123dBA, this only required 8 strikes before posing a significant risk to hearing.

INTRODUCTION

The popularity of Golf has seen significant increases in the past 25 years, particularly in Europe and the United States. In the U.K. alone figures from 2011 showed 1.3 million golf players and close to 3000 golf courses [1]. Golf requires the player to swing various types of clubs to hit balls into a relatively wide open space with the ultimate aim of sending the ball into a hole with the least amount of shots.

Golf is perceived as a low-risk sport compared with other sports such as rugby, football, basketball or skiing that have higher injury rates, however several studies have provided insight into injuries related to golf. These range from the common spine and upper or lower limb injuries [2] to the less frequent injuries related to golf ball trauma [3].

Golf has not been attributed to leisure noise exposure and noise induced hearing loss (NIHL) until recently [4]. Noise can be described as sound at an intensity that can interfere with verbal communication and may cause discomfort of the ears or reduction of hearing sensitivity, defined as hearing damage [5]. Any exposure to noise of significant intensity and duration increases the risk of ear damage and causes permanent hearing damage, known as noise induced hearing loss (NIHL). Both industrial noise exposure and noise in leisure are the major causes of avoidable permanent hearing loss throughout the world. Within the categories of leisure noise, noise exposure from sporting activities is a major recreational noise sources relevant to various social activities, such as, motor sport [6], shooting [7], and spectators at a football match [8].

A study that investigated the potential hazard of modern Driver golf clubs in damaging users hearing from excessive exposure to loud sounds has highlighted this link [4]. They reported on a case of a 55 year old man who had appeared to developed unilateral noise induced hearing loss due to the exposure of loud noises generated from his driver golf club. When using a professional golfer, they found that many of the clubs generated sounds in excess of 120dBA, particularly the thin faced titanium drivers. Therefore, the authors recommended caution should be exercised by any golfers using the thin faced titanium drivers to avoid damage to their hearing.

This raises a number of interesting questions. The use of a sound level meter (SLM) equidistant from the golfer provided information in the free field. However, in using a SLM it is unclear what acoustical effects the ear canal resonance would have on the noise generated. Further, the methods used previously did not provide ear specific information and whether the head shadow effect was implicated. In having one professional take part in the study it was unclear if this could be applied to amateur golfers, and whether the sound generated correlated with swing speed. So, there is uncertainty of the immediate and long-term dangers of such issues in Golf, and a significant knowledge gap remains regarding effective guidance on hearing health awareness and prevention of this sport leisure noise damage to hearing. Therefore, the aim of this study was to further investigate the acoustical characteristics in situ using real ear measurement using various driver clubs. The relationship between swing speed and the noise levels generated was also investigated.

MATERIAL AND METHOD

Participants

19 male participants volunteered to take part in the study, with an age range of 19-54 years (mean 38 years). Of the 19 participants, 2 were left handed and 17 right handed. Each participant had at least 2 years of golfing experience, with no history of industrial noise exposure or recent ear infection.

Audiological investigation

All participants completed a brief questionnaire, otoscopic examination, and pure tone audiometry measurement. Pure tone hearing thresholds were measured for both ears at the frequencies 250, 500, 1,000, 2,000, 3,000 4,000, 6,000 and 8,000 Hz, using a calibrated Essilor Audioscan audiometer with DT 48 headphones. The procedure followed was that recommended by the British Society of Audiology [9]. The background ambient noise level was approximately 35-40 dBA.

Measurement of peak sound pressure levels in situ

Three different branded clubs (coded as Club1, Club 2 and Club3) were used in the study along with the participants own club (Club 0). The three clubs chosen were reflective of modern technology and incorporating some of the clubs used in a previous study [4]. Following a warm-up period, the participants were asked to choose the clubs in a random order and hit 6 two-piece range golf balls with each club.

The frequency responses and peak sound pressure levels in situ of the transient sound generated from the club at impact were recorded bilaterally using the GN Otometric Freefit wireless Real Ear Measurement System (REM). Probe placement was 25mm along the external auditory canal [10]. Room and probe tube calibration were carried out before each participant. All recordings were completed at a golf driving range in South Wales, UK.

For the purpose of measuring the real ear acoustic characteristics in situ when the golfer was striking the ball and to allow comparisons based on dexterity, a label of far and near ear was used. This was implemented because it was unclear if there were differences between the right and left ears due to their distances from the ball, which would be determined by the position of each ear exposed to the ball depending on the golfer's dexterity. In essence the ball is positioned opposite the leading foot when using a driver club to promote an upward impact and trajectory. Therefore, right-handed golfers had their left ear defined as the near ear, while the right ear was defined as the far ear and vice versa for the left handed golfers (Figure 1).

[Insert Figure 1]

Swing speed measurement

The participant swing speed was recorded using the Swing Speed Radar® system. The unit houses a small microwave Doppler radar velocity sensor that provides an accurate measurement of club head speed at impact. The unit was position within 6 inches of the ball and in line with the swing plane.

Ethics

The study gained ethical approval from the Graduate School of Education (GSoE), University

of Bristol. All participants were informed about the purpose, potential risks of the study, their roles and rights as participants, the nature of the study; and issues of confidentiality and anonymity of the data. Participation was on a voluntary basis and information was provided regarding withdrawal from the study at any time. With the possibility of detecting hearing loss through the audiological evaluation, participants were provided with a copy of the hearing test and informed if they needed to consult with their General Practitioner for further investigation.

Statistical design and analyses

Collected data was stored in an Excel database and all relevant analyses were carried out on Statistical Package for Social Science (SPSS) version 19.0 for Windows software.

RESULTS

1. General information and hearing thresholds

Of the 19 amateur golfers who participated in the study, 10 had less than 10 years experience (53%), 6 participants had golfing experience between 10 and 20 years (31%), three participants had more than twenty years experience (16%). Table 1 provides the mean hearing levels over the frequency range from 0.25 to 8 kHz. A paired t-test results showed that the mean pure tone thresholds did not differ significantly.

Subject	Age	Height	Dexterity	Time playing	Driver	Near ear average threshold	Far ear average threshold
1	43	5.10"	Right	2-5 years	Taylormade 2.0	9	8
2	30	6.0"	Left	5-10 years	Taylormade R9	8	6
3	29	6.3"	Right	5-10 years	Misushiba V-Max	3	2
4	33	5.9"	Right	>20 years	Taylormade R5	8	19
5	41	6.0"	Right	10-20 years	Nike Sashquash	10	10
6	32	5.10"	Right	5-10 years	Mizuno MP001	6	4
7	42	5.10"	Left	5-10 years	Titleist 909 D	4	11
8	50	5.11"	Right	10-20 years	King Cobra L4V	8	8
9	54	5.11"	Right	>20 years	Ping G2	8	9
10	34	6.0"	Right	10-20 years	Titleist 910 D3	2	4
11	29	6.0"	Right	10-20 years	Titleist 907 D1	6	6
12	36	6.2"	Right	5-10 years	Taylormade 2.0	4	4
13	28	6.1"	Right	10-20 years	Ping G5	2	1
14	33	6.0"	Right	5-10 years	Titleist D1	14	6
15	47	6.0"	Right	2-5 years	Titleist 983	12	21
16	48	5.7"	Right	10-20 years	Mizuno MX560	11	4
17	35	5.10"	Right	5-10 years	Taylormade R11	6	5
18	50	5.7"	Right	>20 years	Ping G5	13	14
19	19	5.9"	Right	5-10 years	Titleist 910 D2	3	4

Table 1: General information for participants.

2. Real ear acoustical characteristics of sound impulses generated by golf drivers

Three popular golf drivers together with the participant's individual driver were used for the experiment. Figure 2 shows the averaged sound pressure level (SPLs) in the far and near ears generated by the golf drivers.

[Insert Figure 2]

The averaged SPLs were 85-88 dBA while using club 2, 3 and the varied drivers that belong to the participants. However, the averaged SPL for club 1 was approximately 100 dBA. A one-way repeated measure ANOVA was conducted to compare the sound levels generated from the different golf clubs and to investigate the dB recorded in each ear. There was a significant effect for club, Wilks' Lambda = .06, F (3, 16)=85.01, p< .0005. Post-hoc comparisons using the Tukey HSD test for mean score of club 1 (M = 99.114, SE 1.189) was significantly different from every other club at the .0005 significance level. None of the other clubs were significantly different from each other. The main effect for ear, Wilks' Lambda= .89, F (1, 18) =3.318, p=.085] did not reach statistical significance.

Furthermore, frequency analysis showed that the different golf drivers had different frequency characteristics, as shown in figure 3.

[Insert Figure 3]

In the present study, club 2 and 3 had similar peak frequency characteristics when striking the balls that were around 3.5 kHz, while the average peak frequency characteristics of club 1 was 2.5 kHz. . A one-way repeated measure ANOVA was conducted to compare the peak frequency generated from the different golf clubs and to investigate the peak frequency recorded in each ear. There was a significant effect for club, Wilks' Lambda = .33, F (3, 111)=74.22, *p*< 0.0005. Post-hoc comparisons using the Tukey HSD test for mean score demonstrated club 1 (M = 2511.136, SE 28.02) was significantly different from every other club at the .0005 significance level. Club 4 was also statistically different from every club (M= 2982.557, SE 93.767) at the 0.0005 significance level. The main effect for ear, Wilks' Lambda= 0.89, F (3, 111) =74.22, *p*< 0.0005 was also statistical significant.

3. Correlation between the sound intensity and swing speed

Figure 4 shows the averaged swing speed when using different golf drivers. Similar swing speeds were found across with an average of 167.9 kph.

[Insert Figure 4]

The relationship between sound intensity (dB level) and swing speed (kph) was investigated using Pearson product-moment correlation coefficient. There was a small, positive correlation between the two variables, but no statistical significance was found (r= 0.29, *p*=0.228).

4. Hearing risk estimation by calculating the percentage of daily noise exposure for hitting a basket of golf balls

Hearing risk was estimated by calculating the percentage of daily noise exposure for hitting a basket of golf balls using the drivers described above. The sound duration of striking a golf ball was recorded at 0.5 seconds. If hitting a basket of golf balls, which are typically 40 in number, the total sound exposure duration was 20 seconds (i.e., 0.00556 hours). Thus, the formula used in the present study was

$$\%= T_1/T$$

Where T=8/2^((SPL-85)/3)

On the basis of the SPLs measured in the present study, the percentage of daily noise exposure for hitting a basket of golf balls using the drivers described above were less than 2.5% (Figure 5). For instance, 1800 balls wound generate noise damage if they all gave 100dBA output to the ear canal. Interestingly, an impact noise of 116dBA average over a basket of balls (40) provided the 100% exposure limit. Of the 228 recorded dB responses for the near and far ear for club 1, 4 in the far ear and 3 in the near ear were in excess of 116dBA. Participant 7 had the maximum dB level recorded at 123dBA, and all 3 near ear recordings above 116dBA were attributed to him (122, 123, 123dBA). When using club 1 and a level of 123dBA, the risk to hearing is significant once only 8 balls have been struck.

[Insert Figures 5 & 6]

DISCUSSION

Although a small sample of clubs was used in the present study, and therefore the findings cannot be attributed to all driver clubs on the market, it does demonstrate that there is significant variance in the output generated from thin faced titanium drivers, with the output from club 1 significantly higher than the others. The findings in this study can be contrasted with an earlier report using a professional golfer to hit three balls with six thin faced titanium drivers [4]. Their results showed that all three strikes of each of the six clubs were in the region of 120-130 dB. We know from the calculation used in our study that only a few balls hit at these intensities is needed to cause noise induced hearing loss. However, the results derived from this study with 19 amateur golfers will provide some reassurance that the noise levels generated on the whole are not a significant risk. In a typical round of golf, the driver would be used between 12-18 times. Of our 19 amateur participants, 79% report that they play golf 1-2 times per week on separate days. All but one participant use the driving range less than 3 times a week, with 67% hitting 10 or less balls with the driver. These findings would imply that the risks are, on the whole, negligible. However, the exposure analysis completed on the highest generator of noise, club 1, does provide important insight. At the maximum value of 123dBA, only 8 balls would be needed for hearing damage. Interestingly, subject 7 who recorded this value uses the range 3-4 times per week and would hit 11-20 balls with the driver. Of the six strikes with club 1, subject 7 had 3 recordings in excess of 120 dB in the near ear (122, 123 & 123). On the basis that half of the strikes would be close to 123dB, a typical visit to the range using club 1 would result in 5-10 strikes generating noise that would pose a significant risk of noise induced hearing loss in the near ear. This would fit with the case study of an amateur golfer presenting with unilateral hearing loss [4]. It is worth noting that subject 7's own club was not the same as club 1.

The results did not provide evidence of a head shadow effect in that there was not a significant difference between the recordings from the near and far ear. This is surprising considering that head diffraction increases with increasing frequency because of the increasingly shorter wavelengths [12], with the average frequencies generates between 2.5 and 3.5 kHz in this study. There are number of possible explanations for this. The published work on head diffraction [12] has used a stationary object to cast the acoustic shadow. The speed at which the golf swing starts and finishes and the movement of the torso and the head mean that the exposure to the impact noise generated is spread across the two ears. At impact the torso is uncoiling and moments later the body and head move to a position where both ears face the impact zone. It would appear from the group results of this study that the movement is so quick that one ear is not overly exposed and therefore, we would not expect a unilateral hearing loss to develop from using a golf driver. However, that expectation is based on an assumption that all golfers have a similar result from their swing. It is possible that an individual swings a driver and keeps the head completely stationary throughout impact and the entirety of the swing. However, if this was the case, it would unlikely be an effective swing that would restrict weight transfer and momentum and therefore unlikely generate high levels of noise.

Swing speed was shown to have a small positive but non-significant correlation with noise levels generated. A variable that was uncontrollable in this study was area of the club face the ball made impact. The face of the driver club has a 'sweet spot' where the trampoline effect is optimal. An investigation of strikes out of the heel, toe and sweet spot using an automated and controlled swing motion with a robot [11] would add valuable insight into this enquiry, particularly when comparisons are made from amateurs and professional golfers. It is expected that swing speed and frequency of impact on the sweet spot would be significantly higher in professional golfers compared to amateurs.

CONCLUSION

The immediate danger of noise induced hearing loss for amateur golfers is relatively small. However, this is dependent on exposure time and the more balls that are struck the greater chance of excessive exposure. It is unclear what the long-term risks are. A large scale longitudinal study that recorded hearing thresholds would provide a valuable insight.

ACKNOWLEDMENTS, COMPETING INTERESTS, FUNDING & DATA SHARING

This study was supported by the Great Britain Sasakawa (application number B68) and GN Otometrics. There are no competing interests addition data is available by emailing the contact author.

CONTRIBUTORSHIP

B Bardsley developed the idea, designed the study, collected the data, analysed the data and wrote the article.
F Zhao wrote the grant application, designed the study, collected the data, revised the artilce.
F Zhao is the guarantor.

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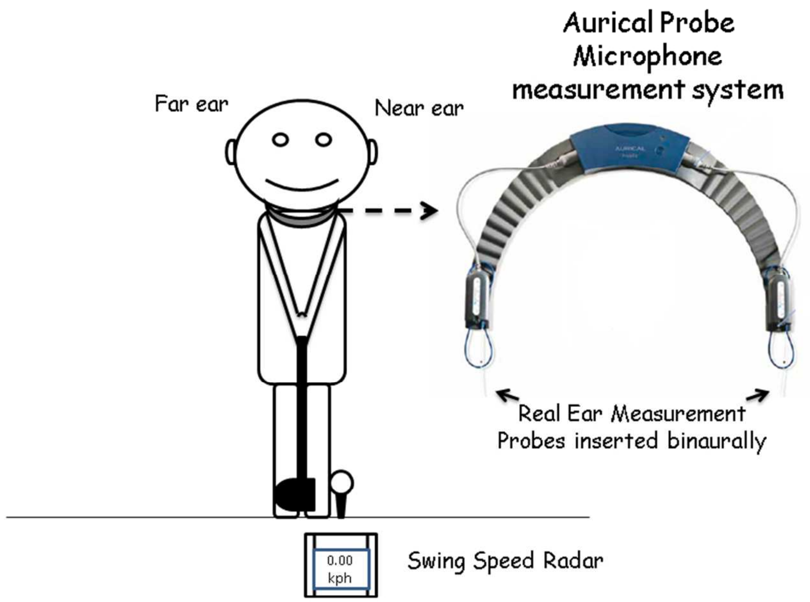
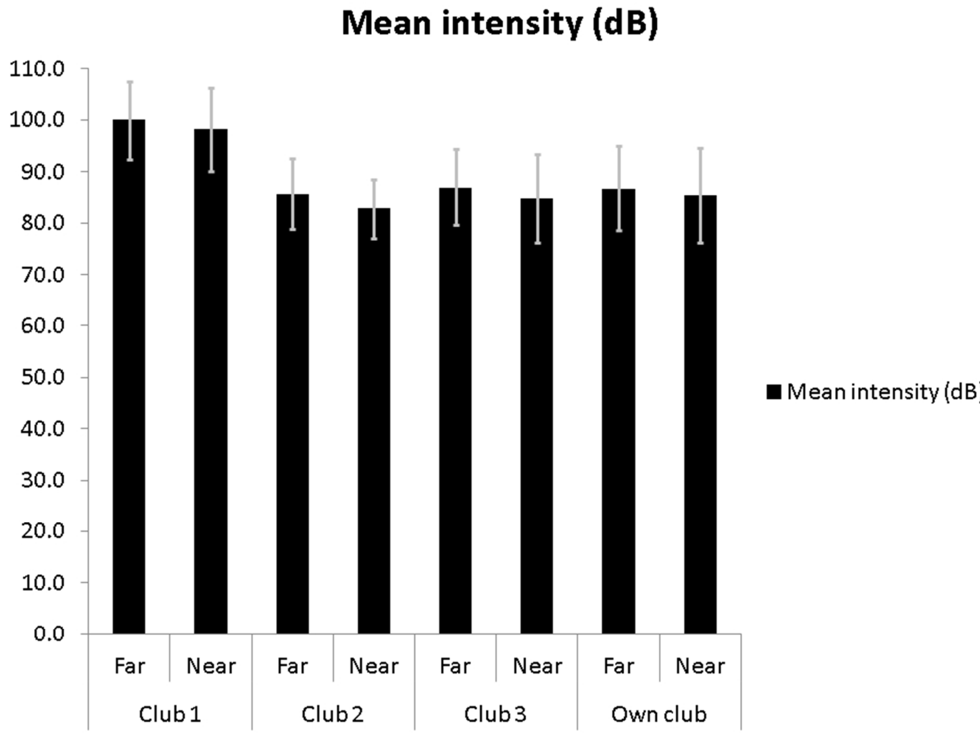
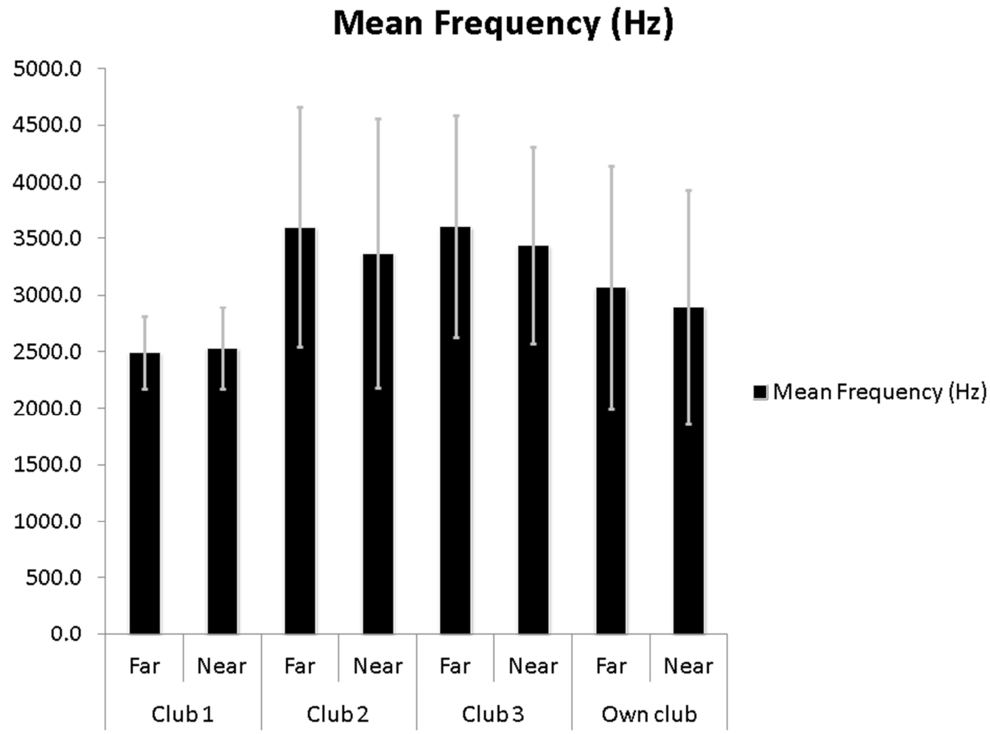


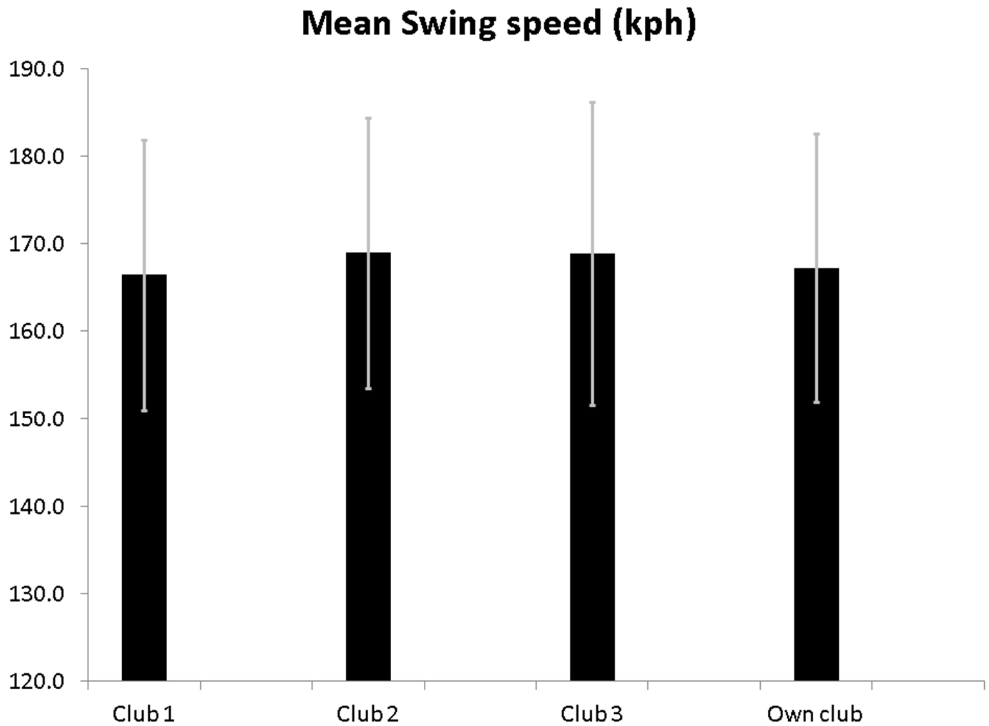
Experimental set-up
254x190mm (96 x 96 DPI)



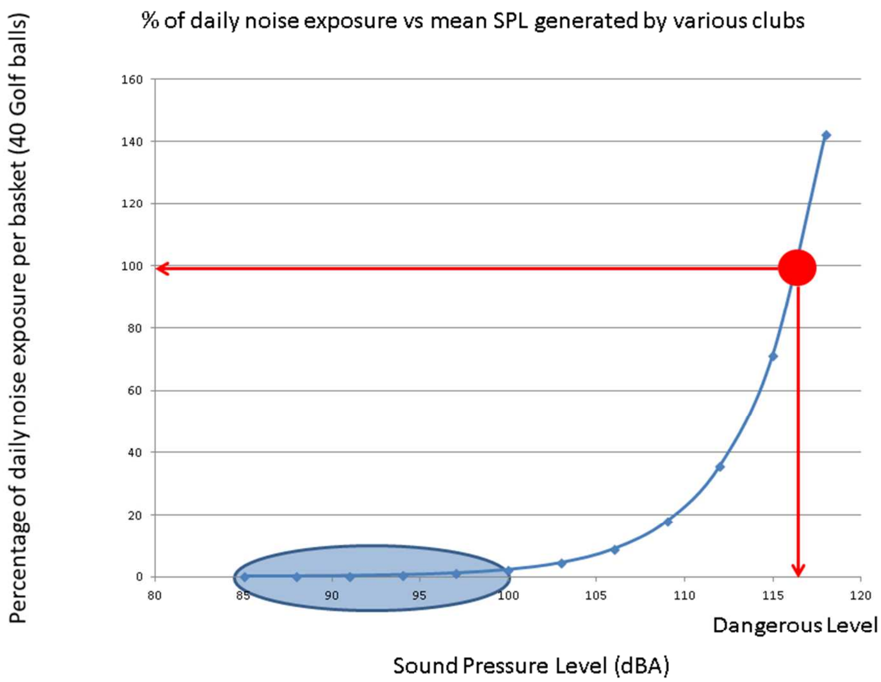
Mean intensity with standard deviation for each ear of each of the clubs
254x190mm (96 x 96 DPI)



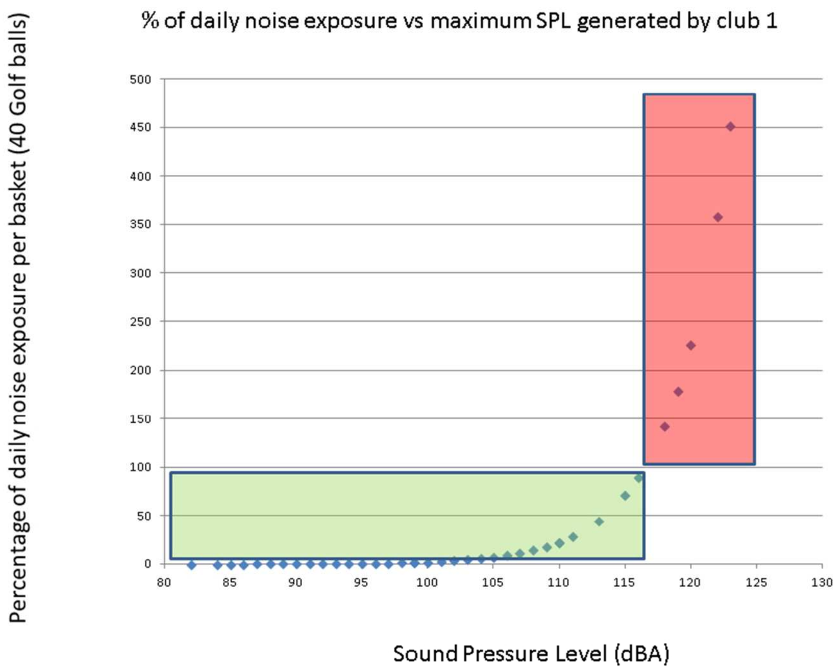
Peak frequency with standard deviation for each ear of each of the clubs
254x190mm (96 x 96 DPI)



Swing speed mean with standard deviation for each club
254x190mm (96 x 96 DPI)



Daily noise exposure calcuated from a basket of 40 golf balls
254x190mm (96 x 96 DPI)



Daily noise exposure plotted against the maximum sound pressure level from club 1 using 40 balls
254x190mm (96 x 96 DPI)

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Keywords: Golf, Sports Injuries, Noise, Hearing

ABSTRACT

Objectives

This study investigated real ear acoustical characteristics in terms of the sound pressure levels (SPLs) and frequency responses in situ generated from golf club drivers at impact with a golf ball. The risk of hearing loss caused by hitting a basket of golf balls using various drivers was then estimated.

Design:

Cross-sectional study.

Setting:

The three driver clubs were chosen on the basis of reflection of the commonality and modern technology of the clubs. The participants were asked to choose the clubs in a random order and hit 6 two-piece range golf balls with each club. The experiment was carried out at a golf driving range in South Wales, UK.

Participants:

Nineteen male amateur golfers volunteered to take part in the study, with an age range of 19-54 years.

Outcome measures:

The frequency responses and peak sound pressure levels in situ of the transient sound generated from the club at impact were recorded bilaterally and simultaneously using the GN Otometric Freefit wireless Real Ear Measurement System (REM). A Swing Speed Radar system was also used to investigate the relationship between noise level and swing speed.

Results:

Different clubs generated significantly different real ear acoustical characteristics in terms of sound pressure levels and frequency responses. However, they did not differ significantly between the ears. No significant correlation was found between the swing speed and noise

intensity. On the basis of the SPLs measured in the present study, the percentage of daily noise exposure for hitting a basket of golf balls using the drivers described above were less than 2.0%.

Conclusions

The immediate danger of noise induced hearing loss for amateur golfers is quite unlikely. However, it may be dangerous to hearing if the noise level generated by the golf clubs exceeded 116 dBA.

ARTICLE SUMMARY

Article focus

1. Is there a risk to hearing for amateur golfers when using the driver golf club?
2. If so, is this risk more prominent in one ear or equal across ears?
3. Does the speed of the swing influence the sound generated?

Key Messages

1. The results indicate varying levels of noise produced by clubs but negligible risk to hearing of amateur golfers, with a daily noise exposure less than 2.0% when averaging the results of the loudest club.
2. No difference was found between ears.
3. Swing speed does not have a significant correlation to the sound generated.

Strengths

An innovative approach taken by using in-the-ear recordings that provide sound pressure levels at the tympanic membrane. This provides a more accurate estimation because it takes ear canal resonance properties into consideration, whereas the alternative of using a sound level meter equidistant does not provide this detail.

Limitations

Limited clubs as well as a small sample size the participants own club meant of golf clubs was used in the study.

INTRODUCTION

The popularity of Golf has seen significant increases in the past 25 years, particularly in Europe and the United States. In the U.K. alone figures from 2011 showed 1.3 million golf players and close to 3000 golf courses.[1] By the nature of the game, Golf requires the player to swing various types of clubs to hit balls into a relatively wide open space with the ultimate aim of sending the ball into a hole with the fewest number of shots. Therefore, Golf is perceived as a low-risk sport compared with other highly competitive sports such as rugby, football, basketball or skiing that have higher injury rates.

However, several studies have shown insight into injuries related to golf. These range from common spine and upper or lower limb injuries to the less frequent injuries related to golf ball trauma.[2,3] In addition, Golf has not been attributed to leisure noise exposure and noise induced hearing loss (NIHL) until recently.[4] Noise can be described as sound at an intensity that can interfere with verbal communication and may cause discomfort of the ears or reduction of hearing sensitivity, defined as hearing damage.[5,6] Any exposure to noise of significant intensity and duration increases the risk of ear damage and causes permanent hearing damage, known as noise induced hearing loss (NIHL). Both industrial noise exposure and noise in leisure are the major causes of avoidable permanent hearing loss throughout the world. Within the categories of leisure noise, noise exposure from sporting activities is a major recreational noise sources relevant to various social activities, such as, motor sport, shooting, and spectators at a football match.[7-9]

A study that investigated the potential hazards of modern driver golf clubs in damaging users' hearing from excessive exposure to loud sounds has highlighted this link.[4] The authors reported on a case of a 55 year old man who had appeared to developed unilateral noise induced hearing loss due to the exposure of loud noises generated from his driver golf club.

When using a professional golfer, they found that many of the clubs generated sounds in excess of 120dBA, particularly the thin faced titanium drivers. Therefore, the authors recommended caution should be exercised by any golfers using the thin faced titanium drivers to avoid damage to their hearing.

This raises a number of interesting questions. The use of a sound level meter (SLM) equidistant from the golfer provided information in the free field. However, in using a SLM it is unclear what acoustical effects the ear canal resonance would have on the noise generated. Further, the methods used previously did not provide ear specific information and whether the head shadow effect was implicated. In having one professional take part in the study it was unclear if this could be applied to amateur golfers, and whether the sound generated correlated with swing speed. So, there is uncertainty of the immediate and long-term dangers of such issues in Golf, and a significant knowledge gap remains regarding effective guidance on hearing health awareness and prevention of this sport leisure noise damage to hearing. Therefore, the aim of this study was to further investigate the acoustical characteristics in situ using real ear measurement using various driver clubs. The relationship between swing speed and the noise levels generated was also investigated.

MATERIAL AND METHOD

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one participant used the driving range less than 3 times a week.

Golf driver clubs

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All recordings were completed at a golf driving range in South Wales, UK.

For the purpose of measuring the real ear acoustic characteristics in situ when the golfer was striking the ball, and to allow comparisons based on dexterity, a label of far and near ear was used. This was implemented because it was unclear if there were differences between the right and left ears due to their distances from the ball, which would be determined by the position of each ear exposed to the ball depending on the golfer's dexterity. In essence the ball was positioned opposite the leading foot when using a driver club to promote an upward impact and trajectory. Therefore, right-handed golfers had their left ear defined as the near ear, while the right ear was defined as the far ear and vice versa for the left handed golfers (Figure 1).

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All recorded real ear responses were reviewed and analysed. In the present study, the peak SPL was determined as the highest point of the curve, whereas the frequency response was referred to as the point corresponding to the measured peak SPL. Both peak SPL and frequency response were chosen from visual inspection by the authors, and then measured directly in the real ear response curves.

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The participant swing speed was recorded using the Swing Speed Radar® system. The unit houses a small microwave Doppler radar velocity sensor that provides an accurate measurement of club head speed at impact. The unit was position within 6 inches of the ball and in line with the swing plane.

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of Bristol. All participants were informed about the purpose, potential risks of the study, their roles and rights as participants, the nature of the study; and issues of confidentiality and anonymity of the data. Participation was on a voluntary basis and information was provided regarding withdrawal from the study at any time. With the possibility of detecting hearing loss through the audiological evaluation, participants were provided with a copy of the hearing test and informed if they needed to consult with their General Practitioner for further investigation.

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RESULTS

I. Real ear acoustical characteristics of sound impulses generated by golf drivers

Figure 2 shows a scatter plot of the averaged sound pressure level (SPLs) obtained in individuals in the far and near ears generated by three golf drivers, which were used for the experiment. The averaged SPLs were approximately 82-88 dBA while using Clubs 2 and 3 (Club 2 far ear and near ear: 85.7 and 82.8 dBA; Club 3 far ear and near ear: 87.0 abd 84.8 dBA), whereas the averaged SPLs for Club 1 were 100.0 and 98.2 dBA on far ears and near ears, respectively (Table 1). The repeated measures ANOVA was conducted to compare the sound levels generated from the different golf clubs and to investigate the dB recorded in each ear. The repeated measures ANOVA results showed that there were significant differences in the SPLs obtained from Clubs 1, 2 and 3 (Wilks' Lambda=0.06, F (2, 17)=134.33, *p*<0.0005). However, no significant differences were found in the SPLs between the far ears and the near ears (F [1, 18] =3.48, *p*=0.08). Further analysis showed that the SPLs generated by Club 1 was significantly greater than those found in Clubs 2 and 3 (*p*<0.0005). In contrast, there was no significant difference in the SPLs between Club 2 and Club 3.

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Furthermore, frequency response analysis showed that the different golf drivers had different frequency characteristics. As shown in Figure 3, Clubs 2 and 3 had similar peak frequency characteristics around 3.5 kHz when striking the balls, while the average frequency response characteristic of Club 1 was 2.5 kHz on either the far ear or the near ear. Although no significant differences were found in frequency responses between the far ears and the near ears (F [1, 18] =2.18, *p*=0.16), the repeated measures ANOVA results showed that the peak frequencies differed significantly among the three clubs (F [2, 17] =38.72, *p*<0.0005). Further analysis showed that the frequency responses found in the Club 1 were significantly lower than those in Clubs 2 and 3 (*p*<0.0005). In contrast, there was no significant difference in the frequency responses between Club 2 and Club 3.

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II. Correlation between sound intensity and swing speed

Table 1 shows the averaged swing speed when using different golf drivers. A one way ANOVA test showed that there were no significant differences in swing speeds between Clubs 1, 2 and 3 (Club 1 vs. Club 2 vs. Club 3: 166.5 vs. 169.0 vs. 168.9, F=0.18, p=0.84). The relationship between sound intensity (dB level) and swing speed (kph) was investigated using the Pearson product-moment correlation coefficient. There was a small, positive correlation between the two variables, but no statistical significance was found ($r_{far\text{-}ear}$= 0.13, p=0.32; $r_{near\text{-}ear}$= 0.05, p=0.72).

III. Hearing risk estimation by calculating the percentage of daily noise exposure for hitting a basket of golf balls

Hearing risk was estimated by calculating the percentage of daily noise exposure for hitting a basket of golf balls using those drivers described above. The sound duration of striking a golf ball was measured by recording the sound waveforms from the beginning of the impulse sound until it fell away when crossing the baseline. On average, the sound duration of striking a golf ball was recorded as approximately 0.5 seconds. If hitting a basket of golf balls, which are typically 40 in number, the total sound exposure duration was 20 seconds (i.e., 0.00556 hours).

In the present study, in order to estimate hearing risk, the damage criteria of 85 dBA for a maximum 8 hour period advocated by the National Institute for Occupational Safety and Health (NIOSH) [11] was adapted with an exchange rate of 3 dB and using the A-weighting scale. Thus, the following formula was used:

***Daily Noise Dose* %= T_1 (total exposure duration)/T (reference duration)*100**

Where T=8/2^((SPL-85)/3), and T_1=0.00556.

Because the sound intensities generated by the golf clubs were recorded and measured in the ear canal, in order to compare them with the NIOSH standard, the transformation from real ear sound pressure levels to free-field equivalent values was performed according to ISO 11904-1[12] (i.e., inversion of the average field-to-eardrum transfer function).

On the basis of the SPLs measured in the present study, the percentage of daily noise exposure for hitting a basket of golf balls using the drivers described above were minimal (0.05- 1.8%) (Figure 4). For instance, when using Club 1, the noise of hitting approximately 2200 balls with SPLs around 99 dBA would reach 100% of the daily noise exposure dose. In addition, by theoretical calculation, the noise level of hitting a basket of balls (40) at 116 dBA appeared to reach the 100% exposure limit.

[Insert Figure 4]

DISCUSSION

Although a small sample of clubs was used in the present study, and therefore the findings cannot be attributed to all driver clubs on the market, it does demonstrate that there is significant variance in the output generated from thin faced titanium drivers used in the present study, showing significant differences in the intensity and frequency characteristics obtained from this Club compared with the others. It implies that golf driver clubs differ in terms of a potential risk to hearing damage. On the basis of the results derived from the present study with 19 amateur golfers, the noise levels generated on the whole (approximately 90.0 on average) do not indicate immediate risk. This is consistent with one previous studies,[13,14] which shows 80-94 dB when measuring accurate hitting sounds using the ArtemiS system, which includes a binaural headset in connection with integrated microphones near the opening of the ear canal. However, the current result is contrasted with an earlier report using a professional golfer to hit three balls with six thin faced titanium drivers,[4] which demonstrated a significantly high noise level in the region of 120-130 dBA, although only a few balls were hit at these intensities in the present study.

Such a discrepancy is mainly due to different measurement methods employed between the study carried out by Buchanan and the present study. Real ear measurement (REM) used in the present study is a common method for measuring SPL near the tympanic membrane.[15] It offers an accurate and objective approach including the individual's real ear acoustic characteristics. By contrast, in the study by Buchanan et al.,[4] the SPL was measured using a sound level meter (SLM) in the free field equidistant from the golfer. The limitation of this measurement is not accurate because the acoustical effects of the ear canal resonance are not taken into account. Moreover, the other key issue is that the SPLs measured in the free field are not the actual SPLs in the ear canal because the baffle effect of head and torso is also important for measuring sound transfer from the free field to the ear. In addition, the skills and power possessed by professional golfers may play a role in generating louder SPLs than is the case for amateur golfers.

Although various studies have suggested that exposure to stimuli exceeding the 100% daily noise dose would cause hearing damage, including a hearing sensitivity reduction, tinnitus, hyperacusis and distortion,[5,6,16] recent research argued the appropriateness of applying industrial risk criteria with recreational noise exposure, because these standards were developed specifically for spectrally dense industrial noise with limited dynamic range as an exposure dose for an 8 hour workday. Therefore, comparisons with industrial standards have to be made with caution. Nevertheless, according to the intensity and noise exposure dose calculation found in the present study, the risks are, on the whole, negligible, i.e., the golf players, particularly amateur players are most unlikely to have hearing damage. However, it is noteworthy that some golf clubs can generate extremely high levels of noise, such as at the maximum value of 123dBA recorded from Club 1 used in the study. With such high noise intensity exposure, it is most likely to pose a significant risk of noise induced hearing loss if the driver is used frequently. This would fit with the case study of an amateur golfer presenting with sigificant hearing loss.[4]

Furthermore, the sound of a golf club hitting a golf ball is one of the influencing factors at a subconscious level on a golfer's perception of quality and his/her choice of equipment, because it provides information on whether the ball was hit correctly. Therefore, golf club manufactures tend to make new models of golf driver clubs using various materials (such as titanium) not only to achieve longer distances, but also to create unique sound characteristics to attract attention. The study by Roberts et al.[17] investigated the relationship between the impact sound and elite golfers' subjective perceptions of a shot. They found a strong relationship between the characteristics of sharpness and loudness of sound, and pleasantness and liveliness of perception. Significantly positive correlations were also obtained between the subjective ratings and parameters of the impact sound such as sound pressure level, loudness level and sharpness. This suggests that the golfers' perceptions are influenced by frequency components, loudness and duration.

In addition, the FFT analysis in the previous study [13] showed different sounds in terms of frequency characteristics and reverberation of the tonal components generated by different clubs when they hit the balls. This is in keeping with the findings of the present study, demonstrating that the peak frequency characteristics recorded from golf driver clubs varied significantly between 2.5 and 3.5 kHz. This is associated with the design (e.g., the structure of the club head) and materials used to make these modern clubs, which have been created by the manufactures in order to achieve a more balanced frequency distribution and thus a better sound quality. However, with such clubs, they are likely to create louder hitting sounds than conventional golf clubs, which potentially causes damage to golfers' hearing.

In the present study, the results did not show evidence of a head shadow effect in that there was not a significant difference between the recordings from the near and far ear. This is consistent with some previous studies on hearing performance between ears in participants in the army having no asymmetrical shooting posture.[18] Although several early studies found that the ear opposite to the dominant hand sustained a more pronounced hearing loss, a recent research study did not reveal a significant preference between ears, irrespective of the dominant hand after recreational firearm use.[8]In addition, no head diffraction effect found in this study can be explained as rapid movement of the torso and the head when swinging the golf club, which means that exposure to the impact noise generated is spread across the two ears. When the torso is uncoiling, the body and head move to a position where both ears face directly into the impact sound sources. Therefore, one side of the ear is overly exposed, and as a consequence, a unilateral hearing loss is unlikely to be developed from playing golf.

Swing speed did not show any significant correlations with either acoustical characteristics measured in the golf driver clubs (i.e., intensity levels and peak frequencies), or golfers' heights. Golfers' skill and power (particularly among professional golfers) may be one of the important influencing factors on swing speed. In addition, it is noteworthy that another important factor is the area of the club face hitting the ball to make an impact because the face of the driver club has a 'sweet spot' where the trampoline effect is optimal. An investigation of strikes out of the heel, toe and sweet spot using an automated and controlled swing motion with a robot [19] would add valuable insight into this enquiry, particularly when comparisons are made between amateur and professional golfers.

CONCLUSION

Different clubs generated significantly different real ear acoustical characteristics in terms of sound pressure levels and frequency responses. On the basis of the SPLs measured in the present study, the immediate danger of noise induced hearing loss for amateur golfers is quite unlikely. However, it is most likely to pose a significant risk of noise induced hearing loss if the driver generates high noise intensity greater than 116 dBA. Provision of detailed information on a club's acoustical characteristics may help consumers choose the appropriate device for their needs, particularly for people who are prone to hearing damage. A longitudinal study monitoring hearing thresholds would provide a valuable insight in terms of the long-term risks to hearing.

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COMPETING INTERESTS

There are no competing interests.

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DATA SHARING

Additional data is available by contacting authors.

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CAPTIONS OF FIGURES

Figure 1 Diagram of experimental settings and equipment used

Figure 2 Scatter plot of averaged sound pressure levels (SPLs) obtained in individuals in the far and near ears generated by three golf drivers.

Figure 3 Scatter plot of averaged frequency responses obtained in individuals in the far and near ears generated by three golf drivers.

Figure 4 Percentage of daily noise exposure when hitting golf balls using the drivers

Real ear acoustical characteristics of impulse sound generated by golf drivers and the estimated risk to hearing

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Keywords: Golf, Sports Injuries, Noise, Hearing

ABSTRACT

Objectives

This study investigated real ear acoustical characteristics in terms of the sound pressure levels (SPLs) and frequency responses in situ generated from golf club drivers at impact with a golf ball. The risk of hearing loss caused by hitting a basket of golf balls using various drivers was then estimated.

Design:

Cross-sectional study.

Setting:

The three driver clubs were chosen on the basis of reflection of the commonality and modern technology of the clubs. The participants were asked to choose the clubs in a random order and hit 6 two-piece range golf balls with each club. The experiment was carried out at a golf driving range in South Wales, UK.

Participants:

Nineteen male amateur golfers volunteered to take part in the study, with an age range of 19-54 years.

Outcome measures:

The frequency responses and peak sound pressure levels in situ of the transient sound generated from the club at impact were recorded bilaterally and simultaneously using the GN Otometric Freefit wireless Real Ear Measurement System (REM). A Swing Speed Radar system was also used to investigate the relationship between noise level and swing speed.

Results:

Different clubs generated significantly different real ear acoustical characteristics in terms of sound pressure levels and frequency responses. However, they did not differ significantly between the ears. No significant correlation was found between the swing speed and noise

intensity. On the basis of the SPLs measured in the present study, the percentage of daily noise exposure for hitting a basket of golf balls using the drivers described above were less than 2.0%.

Conclusions

The immediate danger of noise induced hearing loss for amateur golfers is quite unlikely. However, it may be dangerous to hearing if the noise level generated by the golf clubs exceeded 116 dBA.

ARTICLE SUMMARY

Article focus

1. Is there a risk to hearing for amateur golfers when using the driver golf club?
2. If so, is this risk more prominent in one ear or equal across ears?
3. Does the speed of the swing influence the sound generated?

Key Messages

1. The results indicate varying levels of noise produced by clubs but negligible risk to hearing of amateur golfers, with a daily noise exposure less than 2.0% when averaging the results of the loudest club.
2. No difference was found between ears.
3. Swing speed does not have a significant correlation to the sound generated.

Strengths

An innovative approach taken by using in-the-ear recordings that provide sound pressure levels at the tympanic membrane. This provides a more accurate estimation because it takes ear canal resonance properties into consideration, whereas the alternative of using a sound level meter equidistant does not provide this detail.

Limitations

Limited clubs as well as a small sample size the participants own club meant of golf clubs was used in the study.

INTRODUCTION

The popularity of Golf has seen significant increases in the past 25 years, particularly in Europe and the United States. In the U.K. alone figures from 2011 showed 1.3 million golf players and close to 3000 golf courses.[1] By the nature of the game, Golf requires the player to swing various types of clubs to hit balls into a relatively wide open space with the ultimate aim of sending the ball into a hole with the fewest number of shots. Therefore, Golf is perceived as a low-risk sport compared with other highly competitive sports such as rugby, football, basketball or skiing that have higher injury rates.

However, several studies have shown insight into injuries related to golf. These range from common spine and upper or lower limb injuries to the less frequent injuries related to golf ball trauma.[2,3] In addition, Golf has not been attributed to leisure noise exposure and noise induced hearing loss (NIHL) until recently.[4] Noise can be described as sound at an intensity that can interfere with verbal communication and may cause discomfort of the ears or reduction of hearing sensitivity, defined as hearing damage.[5,6] Any exposure to noise of significant intensity and duration increases the risk of ear damage and causes permanent hearing damage, known as noise induced hearing loss (NIHL). Both industrial noise exposure and noise in leisure are the major causes of avoidable permanent hearing loss throughout the world. Within the categories of leisure noise, noise exposure from sporting activities is a major recreational noise sources relevant to various social activities, such as, motor sport, shooting, and spectators at a football match.[7-9]

A study that investigated the potential hazards of modern driver golf clubs in damaging users' hearing from excessive exposure to loud sounds has highlighted this link.[4] The authors reported on a case of a 55 year old man who had appeared to developed unilateral noise induced hearing loss due to the exposure of loud noises generated from his driver golf club.

When using a professional golfer, they found that many of the clubs generated sounds in excess of 120dBA, particularly the thin faced titanium drivers. Therefore, the authors recommended caution should be exercised by any golfers using the thin faced titanium drivers to avoid damage to their hearing.

This raises a number of interesting questions. The use of a sound level meter (SLM) equidistant from the golfer provided information in the free field. However, in using a SLM it is unclear what acoustical effects the ear canal resonance would have on the noise generated. Further, the methods used previously did not provide ear specific information and whether the head shadow effect was implicated. In having one professional take part in the study it was unclear if this could be applied to amateur golfers, and whether the sound generated correlated with swing speed. So, there is uncertainty of the immediate and long-term dangers of such issues in Golf, and a significant knowledge gap remains regarding effective guidance on hearing health awareness and prevention of this sport leisure noise damage to hearing. Therefore, the aim of this study was to further investigate the acoustical characteristics in situ using real ear measurement using various driver clubs. The relationship between swing speed and the noise levels generated was also investigated.

MATERIAL AND METHOD

Participants

19 male amateur golfers volunteered to take part in the study, with an age range of 19-54 years (mean 38 years). Of them, 2 were left handed and 17 right handed. Ten had less than 10 years experience (53%), six participants had golfing experience between 10 and 20 years (31%), three participants had more than twenty years experience (16%). Approximately 80% of participants reported that they play golf 1-2 times per week on separate days, and all but

one participant used the driving range less than 3 times a week.

Golf driver clubs

The three driver clubs were chosen on the basis of reflection of the commonality and modern technology of the clubs together with consideration of their potentially high loudness levels as listed in the study by Buchannan *et al.*[4] Due to the potential commercial dispute and conflicts of interest, the names of the manufacturers of the clubs were not disclosed, and consequently these differently branded clubs were coded as Club 1, Club 2 and Club 3 in the present study. However, this information can be discussed by contacting the authors if there is any concern about the potential hazard of hearing damage to the golf players. In addition, in accordance with experimental protocol, each participant was invited to bring their own driver and use it along with three other driver clubs.

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III. Hearing risk estimation by calculating the percentage of daily noise exposure for hitting a basket of golf balls

Hearing risk was estimated by calculating the percentage of daily noise exposure for hitting a basket of golf balls using those drivers described above. The sound duration of striking a golf ball was measured by recording the sound waveforms from the beginning of the impulse sound until it fell away when crossing the baseline. On average, the sound duration of striking a golf ball was recorded as approximately 0.5 seconds. If hitting a basket of golf balls, which are typically 40 in number, the total sound exposure duration was 20 seconds (i.e., 0.00556 hours).

In the present study, in order to estimate hearing risk, the damage criteria of 85 dBA for a maximum 8 hour period advocated by the National Institute for Occupational Safety and Health (NIOSH) [11] was adapted with an exchange rate of 3 dB and using the A-weighting scale. Thus, the following formula was used:

Daily Noise Dose %= T_1 (total exposure duration)/T (reference duration)*100

Where T=8/2^((SPL-85)/3), and T_1=0.00556.

Because the sound intensities generated by the golf clubs were recorded and measured in the ear canal, in order to compare them with the NIOSH standard, the transformation from real ear sound pressure levels to free-field equivalent values was performed according to ISO 11904-1[12] (i.e., inversion of the average field-to-eardrum transfer function).

On the basis of the SPLs measured in the present study, the percentage of daily noise exposure for hitting a basket of golf balls using the drivers described above were minimal (0.05- 1.8%) (Figure 4). For instance, when using Club 1, the noise of hitting approximately 2200 balls with SPLs around 99 dBA would reach 100% of the daily noise exposure dose. In addition, by theoretical calculation, the noise level of hitting a basket of balls (40) at 116 dBA appeared to reach the 100% exposure limit.

[Insert Figure 4]

DISCUSSION

Although a small sample of clubs was used in the present study, and therefore the findings cannot be attributed to all driver clubs on the market, it does demonstrate that there is significant variance in the output generated from thin faced titanium drivers used in the present study, showing significant differences in the intensity and frequency characteristics obtained from this Club compared with the others. It implies that golf driver clubs differ in terms of a potential risk to hearing damage. On the basis of the results derived from the present study with 19 amateur golfers, the noise levels generated on the whole (approximately 90.0 on average) do not indicate immediate risk. This is consistent with one previous studies,[13,14] which shows 80-94 dB when measuring accurate hitting sounds using the ArtemiS system, which includes a binaural headset in connection with integrated microphones near the opening of the ear canal. However, the current result is contrasted with an earlier report using a professional golfer to hit three balls with six thin faced titanium drivers,[4] which demonstrated a significantly high noise level in the region of 120-130 dBA, although only a few balls were hit at these intensities in the present study.

Such a discrepancy is mainly due to different measurement methods employed between the study carried out by Buchanan and the present study. Real ear measurement (REM) used in the present study is a common method for measuring SPL near the tympanic membrane.[15] It offers an accurate and objective approach including the individual's real ear acoustic characteristics. By contrast, in the study by Buchanan et al.,[4] the SPL was measured using a sound level meter (SLM) in the free field equidistant from the golfer. The limitation of this measurement is not accurate because the acoustical effects of the ear canal resonance are not taken into account. Moreover, the other key issue is that the SPLs measured in the free field are not the actual SPLs in the ear canal because the baffle effect of head and torso is also important for measuring sound transfer from the free field to the ear. In addition, the skills and power possessed by professional golfers may play a role in generating louder SPLs than is the case for amateur golfers.

Although various studies have suggested that exposure to stimuli exceeding the 100% daily noise dose would cause hearing damage, including a hearing sensitivity reduction, tinnitus, hyperacusis and distortion,[5,6,16] recent research argued the appropriateness of applying industrial risk criteria with recreational noise exposure, because these standards were developed specifically for spectrally dense industrial noise with limited dynamic range as an exposure dose for an 8 hour workday. Therefore, comparisons with industrial standards have to be made with caution. Nevertheless, according to the intensity and noise exposure dose calculation found in the present study, the risks are, on the whole, negligible, i.e., the golf players, particularly amateur players are most unlikely to have hearing damage. However, it is noteworthy that some golf clubs can generate extremely high levels of noise, such as at the maximum value of 123dBA recorded from Club 1 used in the study. With such high noise intensity exposure, it is most likely to pose a significant risk of noise induced hearing loss if the driver is used frequently. This would fit with the case study of an amateur golfer presenting with sigificant hearing loss.[4]

Furthermore, the sound of a golf club hitting a golf ball is one of the influencing factors at a subconscious level on a golfer's perception of quality and his/her choice of equipment, because it provides information on whether the ball was hit correctly. Therefore, golf club manufactures tend to make new models of golf driver clubs using various materials (such as titanium) not only to achieve longer distances, but also to create unique sound characteristics to attract attention. The study by Roberts et al.[17] investigated the relationship between the impact sound and elite golfers' subjective perceptions of a shot. They found a strong relationship between the characteristics of sharpness and loudness of sound, and pleasantness and liveliness of perception. Significantly positive correlations were also obtained between the subjective ratings and parameters of the impact sound such as sound pressure level, loudness level and sharpness. This suggests that the golfers' perceptions are influenced by frequency components, loudness and duration.

In addition, the FFT analysis in the previous study [13] showed different sounds in terms of frequency characteristics and reverberation of the tonal components generated by different clubs when they hit the balls. This is in keeping with the findings of the present study, demonstrating that the peak frequency characteristics recorded from golf driver clubs varied significantly between 2.5 and 3.5 kHz. This is associated with the design (e.g., the structure of the club head) and materials used to make these modern clubs, which have been created by the manufactures in order to achieve a more balanced frequency distribution and thus a better sound quality. However, with such clubs, they are likely to create louder hitting sounds than conventional golf clubs, which potentially causes damage to golfers' hearing.

In the present study, the results did not show evidence of a head shadow effect in that there was not a significant difference between the recordings from the near and far ear. This is consistent with some previous studies on hearing performance between ears in participants in the army having no asymmetrical shooting posture.[18] Although several early studies found that the ear opposite to the dominant hand sustained a more pronounced hearing loss, a recent research study did not reveal a significant preference between ears, irrespective of the dominant hand after recreational firearm use.[8]In addition, no head diffraction effect found in this study can be explained as rapid movement of the torso and the head when swinging the golf club, which means that exposure to the impact noise generated is spread across the two ears. When the torso is uncoiling, the body and head move to a position where both ears face directly into the impact sound sources. Therefore, one side of the ear is overly exposed, and as a consequence, a unilateral hearing loss is unlikely to be developed from playing golf.

Swing speed did not show any significant correlations with either acoustical characteristics measured in the golf driver clubs (i.e., intensity levels and peak frequencies), or golfers' heights. Golfers' skill and power (particularly among professional golfers) may be one of the important influencing factors on swing speed. In addition, it is noteworthy that another important factor is the area of the club face hitting the ball to make an impact because the face of the driver club has a 'sweet spot' where the trampoline effect is optimal. An investigation of strikes out of the heel, toe and sweet spot using an automated and controlled swing motion with a robot [19] would add valuable insight into this enquiry, particularly when comparisons are made between amateur and professional golfers.

CONCLUSION

Different clubs generated significantly different real ear acoustical characteristics in terms of sound pressure levels and frequency responses. On the basis of the SPLs measured in the present study, the immediate danger of noise induced hearing loss for amateur golfers is quite unlikely. However, it is most likely to pose a significant risk of noise induced hearing loss if the driver generates high noise intensity greater than 116 dBA. Provision of detailed information on a club's acoustical characteristics may help consumers choose the appropriate device for their needs, particularly for people who are prone to hearing damage. A longitudinal study monitoring hearing thresholds would provide a valuable insight in terms of the long-term risks to hearing.

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COMPETING INTERESTS

There are no competing interests.

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DATA SHARING

Additional data is available by contacting authors.

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CAPTIONS OF FIGURES

Figure 1 Diagram of experimental settings and equipment used

Figure 2 Scatter plot of averaged sound pressure levels (SPLs) obtained in individuals in the far and near ears generated by three golf drivers.

Figure 3 Scatter plot of averaged frequency responses obtained in individuals in the far and near ears generated by three golf drivers.

Figure 4 Percentage of daily noise exposure when hitting golf balls using the drivers

Table 1

	Club 1	Club 2	Club 3
Sound Pressure Level in the ear canal (dBA)			
Far Ear	**100.3±1.3**	**85.7±1.2**	**87.0±1.3**
Near Ear	**98.2±1.4**	**82.8±1.0**	**84.8±1.6**
Frequency Response in the ear canal (kHz)			
Far Ear	**2.49±0.03**	**3.60±0.01**	**3.60±0.09**
Near Ear	**2.53±0.03**	**3.37±0.11**	**3.44±0.08**
Swing Speed (kph)			

Figure 1

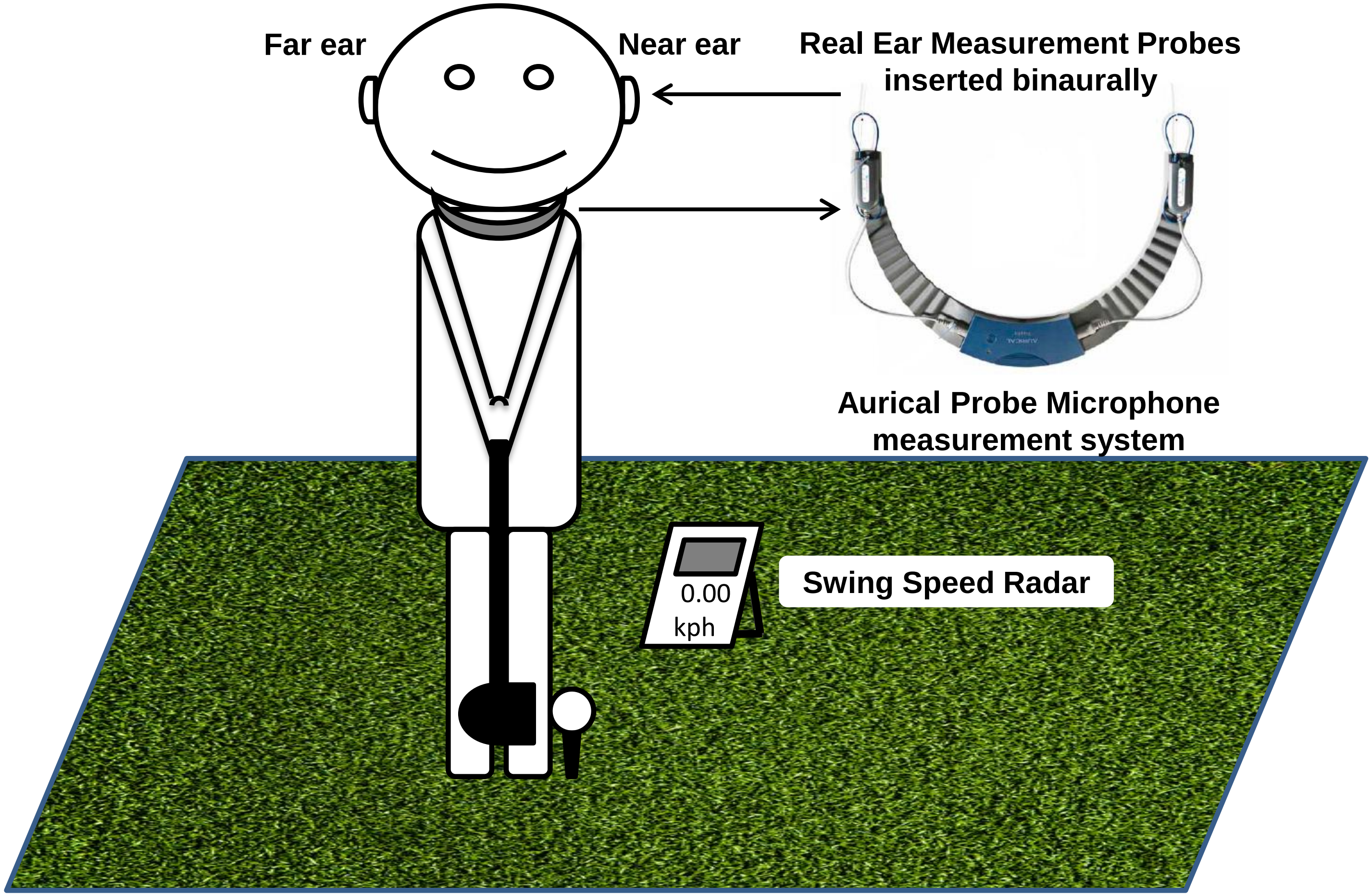

Far ear
Near ear
Real Ear Measurement Probes inserted binaurally
Aurical Probe Microphone measurement system
0.00 kph
Swing Speed Radar

Figure 2

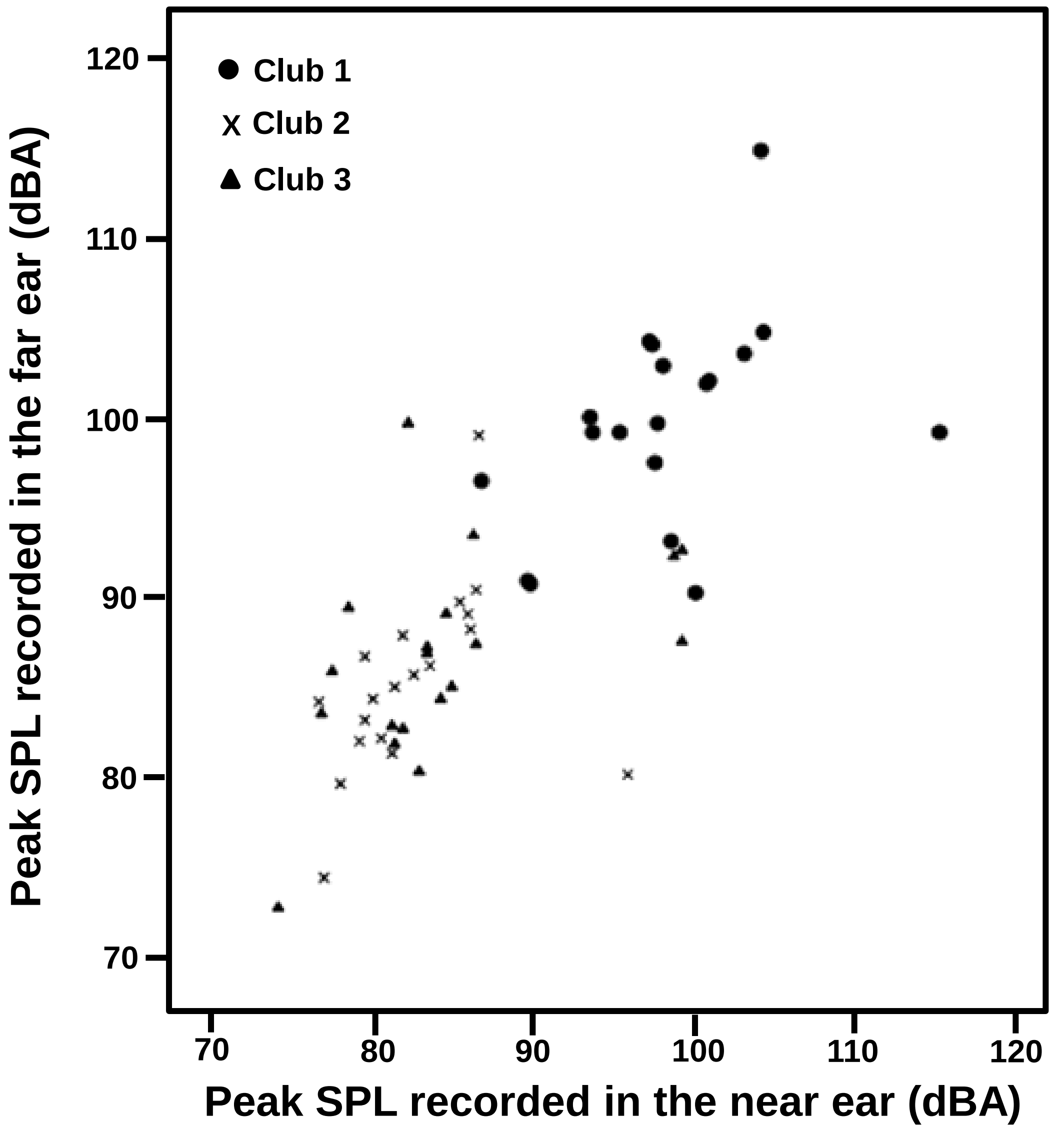

Club 1
Club 2
Club 3
Peak SPL recorded in the far ear (dBA)
Peak SPL recorded in the near ear (dBA)
120
110
100
90
80
70
70
80
90
100
110
120

Figure 3

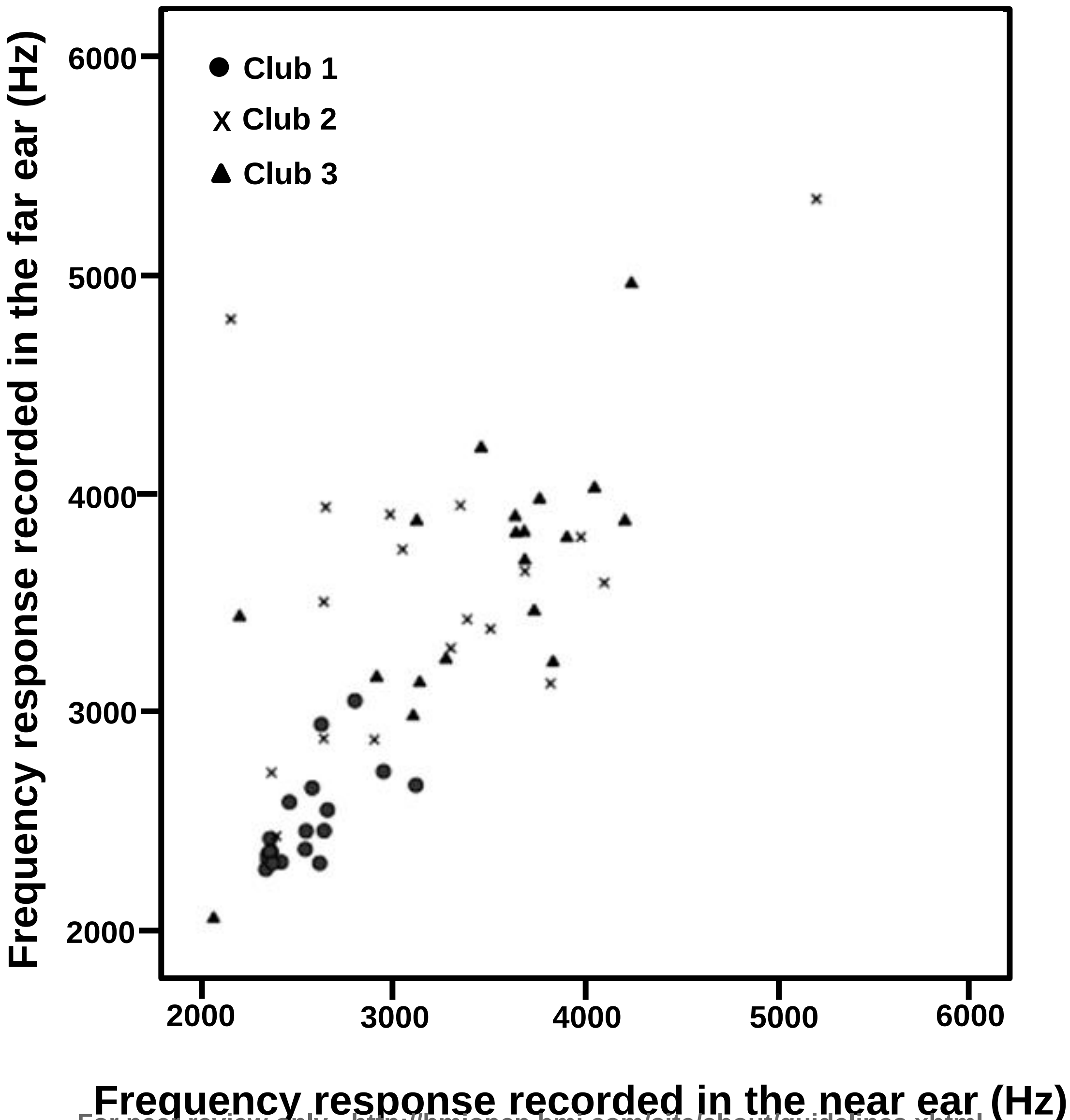
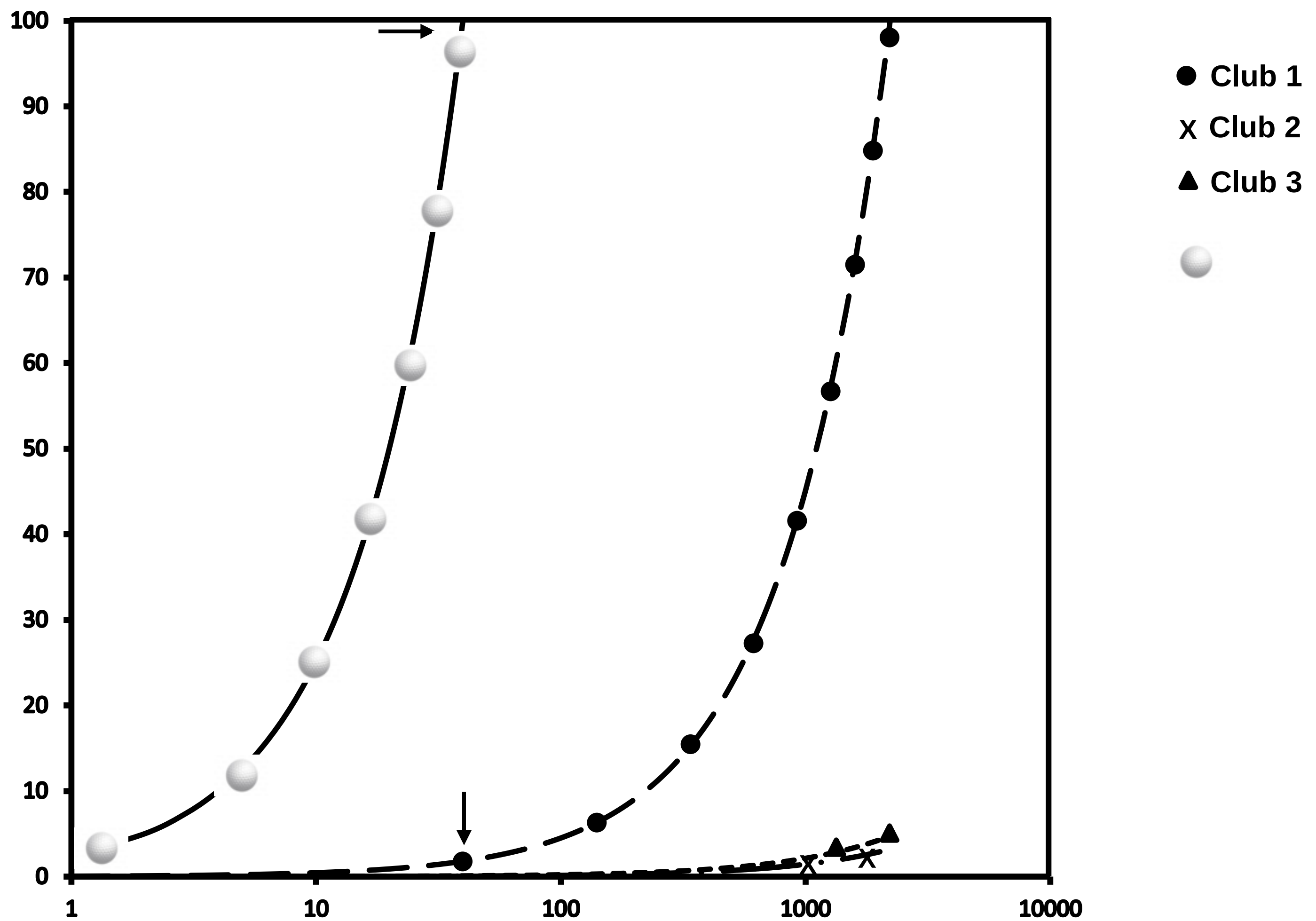

Club 1
Club 2
Club 3
6000
5000
4000
3000
2000
Frequency response recorded in the far ear (Hz)
2000
3000
4000
5000
6000
Frequency response recorded in the near ear (Hz)

Figure 4


100
90
80
70
60
50
40
30
20
10
0
1
10
100
1000
10000
Club 1
Club 2
Club 3

Real ear acoustical characteristics of impulse sound generated by golf drivers and the estimated risk to hearing

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Real ear acoustical characteristics of impulse sound generated by golf drivers and the estimated risk to hearing

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ABSTRACT

Objectives

This study investigated real ear acoustical characteristics in terms of the sound pressure levels (SPLs) and frequency responses in situ generated from golf club drivers at impact with a golf ball. The risk of hearing loss caused by hitting a basket of golf balls using various drivers was then estimated.

Design:

Cross-sectional study.

Setting:

The three driver clubs were chosen on the basis of reflection of the commonality and modern technology of the clubs. The participants were asked to choose the clubs in a random order and hit 6 two-piece range golf balls with each club. The experiment was carried out at a golf driving range in South Wales, UK.

Participants:

Nineteen male amateur golfers volunteered to take part in the study, with an age range of 19-54 years.

Outcome measures:

The frequency responses and peak sound pressure levels in situ of the transient sound generated from the club at impact were recorded bilaterally and simultaneously using the GN Otometric Freefit wireless Real Ear Measurement System (REM). A Swing Speed Radar system was also used to investigate the relationship between noise level and swing speed.

Results:

Different clubs generated significantly different real ear acoustical characteristics in terms of sound pressure levels and frequency responses. However, they did not differ significantly between the ears. No significant correlation was found between the swing speed and noise

intensity. On the basis of the SPLs measured in the present study, the percentage of daily noise exposure for hitting a basket of golf balls using the drivers described above was less than 2.0%.

Conclusions

The immediate danger of noise induced hearing loss for amateur golfers is quite unlikely. However, it may be dangerous to hearing if the noise level generated by the golf clubs exceeded 116 dBA.

ARTICLE SUMMARY

Article focus

1. Is there a risk to hearing for amateur golfers when using the driver golf club?
2. If so, is this risk more prominent in one ear or equal across both ears?
3. Does the speed of the swing influence the sound generated?

Key Messages

1. The results indicate varying levels of noise produced by clubs but negligible risk to hearing of amateur golfers, with a daily noise exposure of less than 2.0% when averaging the results of the loudest club.
2. No difference was found between ears within the same golfer.
3. Swing speed does not have a significant correlation to the sound generated.

Strengths

An innovative approach taken by using in-the-ear recordings that provide sound pressure levels at the tympanic membrane. This provides a more accurate estimation because it takes ear canal resonance properties into consideration, whereas the alternative of using a sound level meter equidistant from the ball does not provide this detail.

Limitations

Only three golf clubs were examined, and a relatively small sample of participants was recruited in the study.

INTRODUCTION

The popularity of Golf has seen significant increases in the past 25 years, particularly in Europe and the United States. In the U.K. alone figures from 2011 showed 1.3 million golf players and close to 3000 golf courses.[1] By the nature of the game, golf requires the player to swing various types of clubs to hit balls into a relatively wide open space with the ultimate aim of sending the ball into a hole with the fewest number of shots. Therefore, golf is perceived as a low-risk sport compared with other highly competitive sports such as rugby, football, basketball or skiing that have higher injury rates.

However, several studies have shown insight into injuries related to golf. These range from common spine and upper or lower limb injuries to the less frequent injuries related to golf ball trauma.[2,3] In addition, golf has not been attributed to leisure noise exposure and noise induced hearing loss (NIHL) until recently.[4] Noise can be described as sound at an intensity that can interfere with verbal communication and may cause discomfort of the ears or reduction of hearing sensitivity, defined as hearing damage.[5,6] Any exposure to noise of significant intensity and duration increases the risk of ear damage and causes permanent hearing damage, known as noise induced hearing loss (NIHL). Both industrial noise exposure and noise in leisure are the major causes of avoidable permanent hearing loss throughout the world. Within the categories of leisure noise, noise exposure from sporting activities is a major recreational noise sources relevant to various social activities, such as, motor sport, shooting, and spectators at a football match.[7-9]

A study that investigated the potential hazards of modern driver golf clubs in damaging users' hearing from excessive exposure to loud sounds has highlighted this link.[4] The authors reported on a case of a 55 year old man who had appeared to have developed unilateral noise induced hearing loss due to the exposure of loud noises generated from his driver golf club. When using a professional golfer, they found that many of the clubs generated sounds in excess of 120dBA, particularly the thin faced titanium drivers. Therefore, the authors recommended caution should be exercised by any golfers using the thin faced titanium drivers to avoid damage to their hearing.

This raises a number of interesting questions. The use of a sound level meter (SLM) equidistant from the golfer provided information in the free field. However, in using a SLM it is unclear what acoustical effects the ear canal resonance would have on the noise generated. Further, the methods used previously did not provide ear specific information and whether the head shadow effect was implicated. In having one professional take part in the study it was unclear if this could be applied to amateur golfers, and whether the sound generated correlated with swing speed. So, there is uncertainty of the immediate and long-term dangers of such issues in golf, and a significant knowledge gap remains regarding effective guidance on hearing health awareness and prevention of this sport leisure noise damage to hearing. Therefore, the aim of this study was to further investigate the acoustical characteristics in situ using real ear measurement using various driver clubs. The relationship between swing speed and the noise levels generated was also investigated.

MATERIAL AND METHOD

Participants

19 male amateur golfers volunteered to take part in the study, with an age range of 19-54 years (mean 38 years). Of them, 2 were left handed and 17 right handed. Ten had less than 10 years experience (53%), six participants had golfing experience between 10 and 20 years

(31%), three participants had more than twenty years experience (16%). Approximately 80% of participants reported that they play golf 1-2 times per week on separate days, and all but one participant used the driving range less than 3 times a week.

Golf driver clubs

The three driver clubs were chosen on the basis of reflection of the commonality and modern technology of the clubs together with consideration of their potentially high loudness levels as listed in the study by Buchanan *et al.*[4] Due to the potential commercial dispute and conflicts of interest, the names of the manufacturers of the clubs were not disclosed, and consequently these differently branded clubs were coded as Club 1, Club 2 and Club 3 in the present study. However, this information can be discussed by contacting the authors if there is any concern about the potential hazard of hearing damage to the golf players. In addition, in accordance with experimental protocol, each participant was invited to bring their own driver and use it along with three other driver clubs.

Measurement of real ear responses

Because of natural amplification of the external ear canal, for the purpose of this study, the real ear acoustical characteristics in terms of sound frequency spectrum (i.e. frequency response) and sound pressure level were investigated using a probe microphone at the position near the eardrum. Following a warm-up period, the participants were asked to choose the clubs in a random order and hit 6 two-piece range golf balls with each club. The frequency responses and peak sound pressure levels in situ of the transient sound generated from the club at impact were recorded bilaterally and simultaneously using the GN Otometric Freefit wireless Real Ear Measurement System (REM). Probe placement was 25mm along the external auditory canal.[10] Room and probe tube calibration were carried out before performing the experiment for each participant.

All recordings were completed at a golf driving range in South Wales, UK.

For the purpose of measuring the real ear acoustic characteristics in situ when the golfer was striking the ball, and to allow comparisons based on dexterity, a label of far and near ear was used. This was implemented because it was unclear if there were differences between the right and left ears due to their distances from the ball, which would be determined by the position of each ear exposed to the ball depending on the golfer's dexterity. In essence the ball was positioned opposite the leading foot when using a driver club to promote an upward impact and trajectory. Therefore, right-handed golfers had their left ear defined as the near ear, while the right ear was defined as the far ear and vice versa for the left handed golfers (Figure 1).

[Insert Figure 1]

All recorded real ear responses were reviewed and analysed. In the present study, the peak SPL was determined as the highest point of the curve, whereas the frequency response was referred to as the point corresponding to the measured peak SPL. Both peak SPL and frequency response were chosen from visual inspection by the authors, and then measured directly in the real ear response curves.

Swing speed measurement

The participant swing speed was recorded using the Swing Speed Radar® system. The unit houses a small microwave Doppler radar velocity sensor that provides an accurate measurement of club head speed at impact. The unit was positioned within 6 inches of the ball and in line with the swing plane.

Ethics

The study gained ethical approval from the Graduate School of Education (GSoE), University of Bristol. All participants were informed about the purpose, potential risks of the study, their roles and rights as participants, the nature of the study; and issues of confidentiality and anonymity of the data. Participation was on a voluntary basis and information was provided regarding withdrawal from the study at any time. With the possibility of detecting hearing loss through the audiological evaluation, participants were provided with a copy of the hearing test and informed if they needed to consult with their General Practitioner for further investigation.

Statistical design and analyses

Collected data was stored in an Excel database and all relevant analyses were carried out on Statistical Package for Social Science (SPSS) version 19.0 for Windows software. A one-way repeated measure ANOVA was performed to examine the effects of golf club (i.e., Clubs 1, 2, 3) and ear side (Far ear, Near ear) on the real ear acoustical characteristics. The mean value and standard deviation of the frequency responses and peak sound pressure levels were calculated and compared using a post-hoc test (i.e., Tukey HSD). A Pearson correlation analysis between swing speed and the real ear acoustical characteristics was also performed. A $p<0.05$ was considered to be statistically significant.

RESULTS

I. Real ear acoustical characteristics of sound impulses generated by golf drivers

Figure 2 shows a scatter plot of the averaged sound pressure level (SPLs) obtained in individuals in the far and near ears generated by three golf drivers, which were used for the experiment. There was a significant correlation in the SPLs recorded between the far and near ears ($r=0.77$, $p<0.0005$). The averaged SPLs were approximately 82-88 dBA while using

Clubs 2 and 3 (Club 2 far ear and near ear: 85.7 and 82.8 dBA; Club 3 far ear and near ear: 87.0 and 84.8 dBA), whereas the averaged SPLs for Club 1 were 100.0 and 98.2 dBA on far ears and near ears, respectively (Table 1). The repeated measures ANOVA was conducted to compare the sound levels generated from the different golf clubs and to investigate the dB recorded in each ear. The repeated measures ANOVA results showed that there were significant differences in the SPLs obtained from Clubs 1, 2 and 3 (Wilks' Lambda=0.06, F (2, 17)=134.33, $p<0.0005$). However, no significant differences were found in the SPLs between the far ears and the near ears (F [1, 18] =3.48, $p=0.08$). Further analysis showed that the SPLs generated by Club 1 were significantly greater than those found in Clubs 2 and 3 ($p<0.0005$). In contrast, there was no significant difference in the SPLs between Club 2 and Club 3.

[Insert Figure 2]

[Insert Table 1]

Furthermore, frequency response analysis showed that the different golf drivers had different frequency characteristics. As shown in Figure 3, there was a significant correlation in the peak frequencies recorded between the far and near ears (r=0.73, $p<0.0005$). Clubs 2 and 3 had similar peak frequency characteristics around 3.5 kHz when striking the balls, while the average frequency response characteristic of Club 1 was 2.5 kHz on either the far ear or the near ear. Although no significant differences were found in frequency responses between the far ears and the near ears (F [1, 18] =2.18, $p=0.16$), the repeated measures ANOVA results showed that the peak frequencies differed significantly among the three clubs (F [2, 17] =38.72, $p<0.0005$). Further analysis showed that the frequency responses found in the Club 1 were significantly lower than those in Clubs 2 and 3 ($p<0.0005$). In contrast, there was no significant difference in the frequency responses between Club 2 and Club 3.

[Insert Figure 3]

II. Correlation between sound intensity and swing speed

Table 1 shows the averaged swing speed when using different golf drivers. A one way ANOVA test showed that there were no significant differences in swing speeds between Clubs 1, 2 and 3 (Club 1 vs. Club 2 vs. Club 3: 166.5 vs. 169.0 vs. 168.9, F=0.18, p=0.84). The relationship between sound intensity (dB level) and swing speed (kph) was investigated using the Pearson product-moment correlation coefficient. There was a small, positive correlation between the two variables, but no statistical significance was found ($r_{far\text{-}ear}$= 0.13, p=0.32; $r_{near\text{-}ear}$= 0.05, p=0.72).

III. Hearing risk estimation by calculating the percentage of daily noise exposure for hitting a basket of golf balls

Hearing risk was estimated by calculating the percentage of daily noise exposure for hitting a basket of golf balls using those drivers described above. The sound duration of striking a golf ball was measured by recording the sound waveforms from the beginning of the impulse sound until it fell away when crossing the baseline. On average, the sound duration of striking a golf ball was recorded as approximately 0.5 seconds. If hitting a basket of golf balls, which are typically 40 in number, the total sound exposure duration was 20 seconds (i.e., 0.00556 hours).

In the present study, in order to estimate hearing risk, the damage criteria of 85 dBA for a maximum 8 hour period advocated by the National Institute for Occupational Safety and Health (NIOSH) [11] was adapted with an exchange rate of 3 dB and using the A-weighting scale. Thus, the following formula was used:

***Daily Noise Dose* %= T_1 (total exposure duration)/T (reference duration)*100**

Where T=8/2^((SPL-85)/3), and T_1=0.00556.

Because the sound intensities generated by the golf clubs were recorded and measured in the ear canal, in order to compare them with the NIOSH standard, the transformation from real ear sound pressure levels to free-field equivalent values was performed according to ISO 11904-1[12] (i.e., inversion of the average field-to-eardrum transfer function).

On the basis of the SPLs measured in the present study, the percentage of daily noise exposure for hitting a basket of golf balls using the drivers described above were minimal (0.05- 1.8%) (Figure 4). For instance, when using Club 1, the noise of hitting approximately 2200 balls with SPLs around 99 dBA would reach 100% of the daily noise exposure dose. In addition, by theoretical calculation, the noise level of hitting a basket of balls (40) at 116 dBA appeared to reach the 100% exposure limit.

[Insert Figure 4]

DISCUSSION

Although a small sample of clubs was used in the present study, and therefore the findings cannot be attributed to all driver clubs on the market, it does demonstrate that there is significant variance in the output generated from thin faced titanium drivers used in the present study, showing significant differences in the intensity and frequency characteristics obtained from this type of club compared with the others. It implies that golf driver clubs differ in terms of a potential risk to hearing damage. On the basis of the results derived from the present study with 19 amateur golfers, the noise levels generated on the whole (approximately 90.0 dB on average) do not indicate immediate risk. This is consistent with previous studies,[13,14] which show 80-94 dB when measuring accurate hitting sounds using the ArtemiS system, which includes a binaural headset in connection with integrated microphones near the opening of the ear canal. However, the current result is contrasted with an earlier report using a professional golfer to hit three balls with six thin faced titanium drivers,[4] which demonstrated a significantly high noise level in the region of 120-130 dBA, although only a few balls were hit at these intensities in the present study.

Such a discrepancy is mainly due to different measurement methods employed between the study carried out by Buchanan et al. and the present study. Real ear measurement (REM) used in the present study is a common method for measuring SPL near the tympanic membrane.[15] It offers an accurate and objective approach including the individual's real ear acoustic characteristics. By contrast, in the study by Buchanan et al.,[4] the SPL was measured using a sound level meter (SLM) in the free field equidistant from the golfer. The limitation of this measurement is not accurate because the acoustical effects of the ear canal resonance are not taken into account. Moreover, the other key issue is that the SPLs measured in the free field are not the actual SPLs in the ear canal because the baffle effect of head and torso is also important for measuring sound transfer from the free field to the ear. In addition, the skills and power possessed by professional golfers may play a role in generating louder SPLs than is the case for amateur golfers.

Although various studies have suggested that exposure to stimuli exceeding the 100% daily noise dose would cause hearing damage, including a hearing sensitivity reduction, tinnitus, hyperacusis and distortion,[5,6,16] recent research argued the appropriateness of applying industrial risk criteria with recreational noise exposure, because these standards were developed specifically for spectrally dense industrial noise with limited dynamic range as an exposure dose for an 8 hour workday. Therefore, comparisons with industrial standards have to be made with caution. Nevertheless, according to the intensity and noise exposure dose calculation found in the present study, the risks are, on the whole, negligible, i.e., the golf players, particularly amateur players are most unlikely to have hearing damage. However, it is noteworthy that some golf clubs can generate extremely high levels of noise, such as at the maximum value of 123dBA recorded from Club 1 used in the study. With such high noise intensity exposure, it is most likely to pose a significant risk of noise induced hearing loss if the driver is used frequently. This would fit with the case study of an amateur golfer presenting with sigificant hearing loss.[4]

Furthermore, the sound of a golf club hitting a golf ball is one of the influencing factors at a subconscious level on a golfer's perception of quality and his/her choice of equipment, because it provides information on whether the ball was hit correctly. Therefore, golf club manufactures tend to make new models of golf driver clubs using various materials (such as titanium) not only to achieve longer distances, but also to create unique sound characteristics to attract attention. The study by Roberts et al.[17] investigated the relationship between the impact sound and elite golfers' subjective perceptions of a shot. They found a strong relationship between the characteristics of sharpness and loudness of sound, and pleasantness and liveliness of perception. Significantly positive correlations were also obtained between the subjective ratings and parameters of the impact sound such as sound pressure level, loudness level and sharpness. This suggests that the golfers' perceptions are influenced by frequency components, loudness and duration.

In addition, the FFT analysis in the previous study [13] showed different sounds in terms of frequency characteristics and reverberation of the tonal components generated by different clubs when they hit the balls. This is in keeping with the findings of the present study, demonstrating that the peak frequency characteristics recorded from golf driver clubs varied significantly between 2.5 and 3.5 kHz. This is associated with the design (e.g., the structure of the club head) and materials used to make these modern clubs, which have been created by the manufactures in order to achieve a more balanced frequency distribution and thus a better sound quality. However, with such clubs, they are likely to create louder hitting sounds than conventional golf clubs, which potentially causes damage to golfers' hearing.

In the present study, the results did not show evidence of a head shadow effect insofar as there was no significant difference in sound intensity between the recordings from the near and far ears. There is some controversy about asymmetrical noise exposure even though both ears are exposed directly to impact sound sources. (8,18,19,20) Some previous studies argued that left ear noise-induced hearing losses are predominantly common in the army, because the ear opposite to the dominant hand sustains over exposure mainly due to the shooting posture. [18,19] However, a recent study on hearing performance after recreational firearm use did not reveal a significant preference in terms of temporary threshold shift between ears, irrespective of the dominant hand.[8] The other study by Job et al. [20] showed that the asymmetry of hearing thresholds between the left ear and right ear was not associated with the subject's shooting posture. They suggested that it is most likely due to different intrinsic characteristics in each side of the ears. In addition, no head diffraction effect found in this study can be explained as rapid movement of the torso and the head when swinging the golf club, which means that exposure to the impact noise generated is spread across the two ears. When the torso is uncoiling, the body and head move to a position where both ears face directly into the impact sound sources. Therefore, one side of the ear is overly exposed, and as a consequence, a unilateral hearing loss is unlikely to be developed from playing golf.

Swing speed did not show any significant correlations with either acoustical characteristics measured in the golf driver clubs (i.e., intensity levels and peak frequencies). Golfers' skill and power (particularly among professional golfers) may be one of the important influencing factors on swing speed. It is noteworthy that another important factor is the area of the club face hitting the ball to create an impact because the face of the driver club has a 'sweet spot' where the trampoline effect is optimal. The trampoline effect refers to a pronounced deformation of the club face upon impact followed by a quick restoration to its original dimensions, acting like a slingshot. When the club face hits the ball right on the sweet spot, it results in very high ball speeds. In the present study, it is impossible for the participants to control this factor in order to deliver the same performance with each strike. An investigation of strikes out of the heel, toe and sweet spot using an automated and controlled swing motion with a robot [21] would add valuable insight into this enquiry, particularly when comparisons are made between amateur and professional golfers.

CONCLUSION

Different clubs generated significantly different real ear acoustical characteristics in terms of sound pressure levels and frequency responses. On the basis of the SPLs measured in the present study, the immediate danger of noise induced hearing loss for amateur golfers is quite unlikely. However, it is most likely to pose a significant risk of noise induced hearing loss if the driver generates high noise intensity greater than 116 dBA. Provision of detailed information on a club's acoustical characteristics may help consumers choose the appropriate device for their needs, particularly for people who are prone to hearing damage. A longitudinal study monitoring hearing thresholds would provide a valuable insight in terms of the long-term risks to hearing.

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COMPETING INTERESTS

There are no competing interests.

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DATA SHARING

Additional data is available by emailing Fei.Zhao@bristol.ac.uk. This data is additional information from a questionnaire regarding golf.

CONTRIBUTORSHIP

B Bardsley developed the idea, designed the study, collected the data, analysed the data and wrote the article.

F Zhao wrote the grant application, designed the study, collected the data, revised the artilce. F Zhao is the guarantor.

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CAPTIONS OF FIGURES

Figure 1 Diagram of experimental settings and equipment used

Figure 2 Scatter plot of averaged sound pressure levels (SPLs) obtained in individuals in the far and near ears generated by three golf drivers.

Figure 3 Scatter plot of averaged frequency responses obtained in individuals in the far and near ears generated by three golf drivers.

Figure 4 Percentage of daily noise exposure when hitting golf balls using the drivers

Figure legend:

Arrow label (→): The percentage of daily noise exposure per basket (40 golf balls)

Table 1

	Club 1	**Club 2**	**Club 3**
Sound Pressure Level in the ear canal (dBA)			
Far Ear	**100.3±1.3**	**85.7±1.2**	**87.0±1.3**
Near Ear	**98.2±1.4**	**82.8±1.0**	**84.8±1.6**
Frequency Response in the ear canal (kHz)			
Far Ear	**2.49±0.03**	**3.60±0.01**	**3.60±0.09**
Near Ear	**2.53±0.03**	**3.37±0.11**	**3.44±0.08**
Swing Speed (kph)	**166.5±15.4**	**169.0±15.4**	**168.9±17.3**

Real ear acoustical characteristics of impulse sound generated by golf drivers and the estimated risk to hearing

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ABSTRACT

Objectives

This study investigated real ear acoustical characteristics in terms of the sound pressure levels (SPLs) and frequency responses in situ generated from golf club drivers at impact with a golf ball. The risk of hearing loss caused by hitting a basket of golf balls using various drivers was then estimated.

Design:

Cross-sectional study.

Setting:

The three driver clubs were chosen on the basis of reflection of the commonality and modern technology of the clubs. The participants were asked to choose the clubs in a random order and hit 6 two-piece range golf balls with each club. The experiment was carried out at a golf driving range in South Wales, UK.

Participants:

Nineteen male amateur golfers volunteered to take part in the study, with an age range of 19-54 years.

Outcome measures:

The frequency responses and peak sound pressure levels in situ of the transient sound generated from the club at impact were recorded bilaterally and simultaneously using the GN Otometric Freefit wireless Real Ear Measurement System (REM). A Swing Speed Radar system was also used to investigate the relationship between noise level and swing speed.

Results:

Different clubs generated significantly different real ear acoustical characteristics in terms of sound pressure levels and frequency responses. However, they did not differ significantly between the ears. No significant correlation was found between the swing speed and noise

intensity. On the basis of the SPLs measured in the present study, the percentage of daily noise exposure for hitting a basket of golf balls using the drivers described above ~~were~~ was less than 2.0%.

Conclusions

The immediate danger of noise induced hearing loss for amateur golfers is quite unlikely. However, it may be dangerous to hearing if the noise level generated by the golf clubs exceeded 116 dBA.

ARTICLE SUMMARY

Article focus

1. Is there a risk to hearing for amateur golfers when using the driver golf club?
2. If so, is this risk more prominent in one ear or equal across both ears?
3. Does the speed of the swing influence the sound generated?

Key Messages

1. The results indicate varying levels of noise produced by clubs but negligible risk to hearing of amateur golfers, with a daily noise exposure of less than 2.0% when averaging the results of the loudest club.
2. No difference was found between ears within the same golfer.
3. Swing speed does not have a significant correlation to the sound generated.

Strengths

An innovative approach taken by using in-the-ear recordings that provide sound pressure levels at the tympanic membrane. This provides a more accurate estimation because it takes ear canal resonance properties into consideration, whereas the alternative of using a sound level meter equidistant from the ball does not provide this detail.

Limitations

~~Limited~~ Only three golf clubs were examined, and a relatively ~~a~~ small sample ~~size~~ of ~~the~~ participants was recruited in the study.

~~as well as a small sample size the participants own club meant of golf clubs was used in the study.~~

INTRODUCTION

The popularity of Golf has seen significant increases in the past 25 years, particularly in Europe and the United States. In the U.K. alone figures from 2011 showed 1.3 million golf players and close to 3000 golf courses.[1] By the nature of the game, ~~Golf~~ golf requires the player to swing various types of clubs to hit balls into a relatively wide open space with the ultimate aim of sending the ball into a hole with the fewest number of shots. Therefore, ~~Golf~~ golf is perceived as a low-risk sport compared with other highly competitive sports such as rugby, football, basketball or skiing that have higher injury rates.

However, several studies have shown insight into injuries related to golf. These range from common spine and upper or lower limb injuries to the less frequent injuries related to golf ball trauma.[2,3] In addition, ~~Golf~~ golf has not been attributed to leisure noise exposure and noise induced hearing loss (NIHL) until recently.[4] Noise can be described as sound at an intensity that can interfere with verbal communication and may cause discomfort of the ears or reduction of hearing sensitivity, defined as hearing damage.[5,6] Any exposure to noise of significant intensity and duration increases the risk of ear damage and causes permanent hearing damage, known as noise induced hearing loss (NIHL). Both industrial noise exposure and noise in leisure are the major causes of avoidable permanent hearing loss throughout the world. Within the categories of leisure noise, noise exposure from sporting activities is a major recreational noise sources relevant to various social activities, such as, motor sport, shooting, and spectators at a football match.[7-9]

A study that investigated the potential hazards of modern driver golf clubs in damaging users' hearing from excessive exposure to loud sounds has highlighted this link.[4] The authors reported on a case of a 55 year old man who had appeared to have developed unilateral noise induced hearing loss due to the exposure of loud noises generated from his driver golf club. When using a professional golfer, they found that many of the clubs generated sounds in excess of 120dBA, particularly the thin faced titanium drivers. Therefore, the authors recommended caution should be exercised by any golfers using the thin faced titanium drivers to avoid damage to their hearing.

This raises a number of interesting questions. The use of a sound level meter (SLM) equidistant from the golfer provided information in the free field. However, in using a SLM it is unclear what acoustical effects the ear canal resonance would have on the noise generated. Further, the methods used previously did not provide ear specific information and whether the head shadow effect was implicated. In having one professional take part in the study it was unclear if this could be applied to amateur golfers, and whether the sound generated correlated with swing speed. So, there is uncertainty of the immediate and long-term dangers of such issues in ~~Golf~~golf, and a significant knowledge gap remains regarding effective guidance on hearing health awareness and prevention of this sport leisure noise damage to hearing. Therefore, the aim of this study was to further investigate the acoustical characteristics in situ using real ear measurement using various driver clubs. The relationship between swing speed and the noise levels generated was also investigated.

MATERIAL AND METHOD

Participants

19 male amateur golfers volunteered to take part in the study, with an age range of 19-54

years (mean 38 years). Of them, 2 were left handed and 17 right handed. Ten had less than 10 years experience (53%), six participants had golfing experience between 10 and 20 years (31%), three participants had more than twenty years experience (16%). Approximately 80% of participants reported that they play golf 1-2 times per week on separate days, and all but one participant used the driving range less than 3 times a week.

Golf driver clubs

The three driver clubs were chosen on the basis of reflection of the commonality and modern technology of the clubs together with consideration of their potentially high loudness levels as listed in the study by Buchan~~n~~an *et al.*[4] Due to the potential commercial dispute and conflicts of interest, the names of the manufacturers of the clubs were not disclosed, and consequently these differently branded clubs were coded as Club 1, Club 2 and Club 3 in the present study. However, this information can be discussed by contacting the authors if there is any concern about the potential hazard of hearing damage to the golf players. In addition, in accordance with experimental protocol, each participant was invited to bring their own driver and use it along with three other driver clubs.

Measurement of real ear responses

Because of natural amplification of the external ear canal, for the purpose of this study, the real ear acoustical characteristics in terms of sound frequency spectrum (i.e. frequency response) and sound pressure level were investigated using a probe microphone at the position near the eardrum. Following a warm-up period, the participants were asked to choose the clubs in a random order and hit 6 two-piece range golf balls with each club. The frequency responses and peak sound pressure levels in situ of the transient sound generated from the club at impact were recorded bilaterally and simultaneously using the GN Otometric Freefit wireless Real Ear Measurement System (REM). Probe placement was 25mm along the external auditory canal.[10] Room and probe tube calibration were carried out before performing the experiment for each participant.

All recordings were completed at a golf driving range in South Wales, UK.

For the purpose of measuring the real ear acoustic characteristics in situ when the golfer was striking the ball, and to allow comparisons based on dexterity, a label of far and near ear was used. This was implemented because it was unclear if there were differences between the right and left ears due to their distances from the ball, which would be determined by the position of each ear exposed to the ball depending on the golfer's dexterity. In essence the ball was positioned opposite the leading foot when using a driver club to promote an upward impact and trajectory. Therefore, right-handed golfers had their left ear defined as the near ear, while the right ear was defined as the far ear and vice versa for the left handed golfers (Figure 1).

[Insert Figure 1]

All recorded real ear responses were reviewed and analysed. In the present study, the peak SPL was determined as the highest point of the curve, whereas the frequency response was referred to as the point corresponding to the measured peak SPL. Both peak SPL and frequency response were chosen from visual inspection by the authors, and then measured directly in the real ear response curves.

Swing speed measurement

The participant swing speed was recorded using the Swing Speed Radar® system. The unit houses a small microwave Doppler radar velocity sensor that provides an accurate measurement of club head speed at impact. The unit was positioned within 6 inches of the ball and in line with the swing plane.

Ethics

The study gained ethical approval from the Graduate School of Education (GSoE), University of Bristol. All participants were informed about the purpose, potential risks of the study, their roles and rights as participants, the nature of the study; and issues of confidentiality and anonymity of the data. Participation was on a voluntary basis and information was provided regarding withdrawal from the study at any time. With the possibility of detecting hearing loss through the audiological evaluation, participants were provided with a copy of the hearing test and informed if they needed to consult with their General Practitioner for further investigation.

Statistical design and analyses

Collected data was stored in an Excel database and all relevant analyses were carried out on Statistical Package for Social Science (SPSS) version 19.0 for Windows software. A one-way repeated measure ANOVA was performed to examine the effects of golf club (i.e., Clubs 1, 2, 3) and ear side (Far ear, Near ear) on the real ear acoustical characteristics. The mean value and standard deviation of the frequency responses and peak sound pressure levels were calculated and compared using a post-hoc test (i.e., Tukey HSD). A Pearson correlation analysis between swing speed and the real ear acoustical characteristics was also performed. A $p<0.05$ was considered to be statistically significant.

RESULTS

I. Real ear acoustical characteristics of sound impulses generated by golf drivers

Figure 2 shows a scatter plot of the averaged sound pressure level (SPLs) obtained in individuals in the far and near ears generated by three golf drivers, which were used for the experiment. There was a significant correlation in the SPLs recorded between the far and near ears (r=0.77, *p*<0.0005). The averaged SPLs were approximately 82-88 dBA while using Clubs 2 and 3 (Club 2 far ear and near ear: 85.7 and 82.8 dBA; Club 3 far ear and near ear: 87.0 ~~abd~~ and 84.8 dBA), whereas the averaged SPLs for Club 1 were 100.0 and 98.2 dBA on far ears and near ears, respectively (Table 1). The repeated measures ANOVA was conducted to compare the sound levels generated from the different golf clubs and to investigate the dB recorded in each ear. The repeated measures ANOVA results showed that there were significant differences in the SPLs obtained from Clubs 1, 2 and 3 (Wilks' Lambda=0.06, F (2, 17)=134.33, *p*<0.0005). However, no significant differences were found in the SPLs between the far ears and the near ears (F [1, 18] =3.48, *p*=0.08). Further analysis showed that the SPLs generated by Club 1 ~~was~~ were significantly greater than those found in Clubs 2 and 3 (*p*<0.0005). In contrast, there was no significant difference in the SPLs between Club 2 and Club 3.

[Insert Figure 2]

[Insert Table 1]

Furthermore, frequency response analysis showed that the different golf drivers had different frequency characteristics. As shown in Figure 3, there was a significant correlation in the peak frequencies recorded between the far and near ears (r=0.73, *p*<0.0005). Clubs 2 and 3 had similar peak frequency characteristics around 3.5 kHz when striking the balls, while the average frequency response characteristic of Club 1 was 2.5 kHz on either the far ear or the near ear. Although no significant differences were found in frequency responses between the far ears and the near ears (F [1, 18] =2.18, *p*=0.16), the repeated measures ANOVA results showed that the peak frequencies differed significantly among the three clubs (F [2, 17] =38.72, p<0.0005). Further analysis showed that the frequency responses found in the Club 1 were significantly lower than those in Clubs 2 and 3 (p<0.0005). In contrast, there was no significant difference in the frequency responses between Club 2 and Club 3.

[Insert Figure 3]

II. Correlation between sound intensity and swing speed

Table 1 shows the averaged swing speed when using different golf drivers. A one way ANOVA test showed that there were no significant differences in swing speeds between Clubs 1, 2 and 3 (Club 1 vs. Club 2 vs. Club 3: 166.5 vs. 169.0 vs. 168.9, F=0.18, p=0.84). The relationship between sound intensity (dB level) and swing speed (kph) was investigated using the Pearson product-moment correlation coefficient. There was a small, positive correlation between the two variables, but no statistical significance was found ($r_{far\text{-}ear}$= 0.13, p=0.32; $r_{near\text{-}ear}$= 0.05, p=0.72).

III. Hearing risk estimation by calculating the percentage of daily noise exposure for hitting a basket of golf balls

Hearing risk was estimated by calculating the percentage of daily noise exposure for hitting a basket of golf balls using those drivers described above. The sound duration of striking a golf ball was measured by recording the sound waveforms from the beginning of the impulse sound until it fell away when crossing the baseline. On average, the sound duration of striking a golf ball was recorded as approximately 0.5 seconds. If hitting a basket of golf balls, which are typically 40 in number, the total sound exposure duration was 20 seconds (i.e., 0.00556 hours).

In the present study, in order to estimate hearing risk, the damage criteria of 85 dBA for a maximum 8 hour period advocated by the National Institute for Occupational Safety and Health (NIOSH) [11] was adapted with an exchange rate of 3 dB and using the A-weighting scale. Thus, the following formula was used:

$$\textit{Daily Noise Dose } \textbf{\%} = \mathbf{T_1} \textbf{ (total exposure duration)/T (reference duration)*100}$$

Where $T=8/2^{((SPL-85)/3)}$, *and* $T_1=0.00556$.

Because the sound intensities generated by the golf clubs were recorded and measured in the ear canal, in order to compare them with the NIOSH standard, the transformation from real ear sound pressure levels to free-field equivalent values was performed according to ISO 11904-1[12] (i.e., inversion of the average field-to-eardrum transfer function).

On the basis of the SPLs measured in the present study, the percentage of daily noise exposure for hitting a basket of golf balls using the drivers described above were minimal (0.05- 1.8%) (Figure 4). For instance, when using Club 1, the noise of hitting approximately 2200 balls with SPLs around 99 dBA would reach 100% of the daily noise exposure dose. In addition, by theoretical calculation, the noise level of hitting a basket of balls (40) at 116 dBA appeared to reach the 100% exposure limit.

[Insert Figure 4]

DISCUSSION

Although a small sample of clubs was used in the present study, and therefore the findings cannot be attributed to all driver clubs on the market, it does demonstrate that there is significant variance in the output generated from thin faced titanium drivers used in the present study, showing significant differences in the intensity and frequency characteristics obtained from this Club type of club compared with the others. It implies that golf driver clubs differ in terms of a potential risk to hearing damage. On the basis of the results derived from the present study with 19 amateur golfers, the noise levels generated on the whole (approximately 90.0 dB on average) do not indicate immediate risk. This is consistent with one previous studies,[13,14] which shows 80-94 dB when measuring accurate hitting sounds using the ArtemiS system, which includes a binaural headset in connection with integrated microphones near the opening of the ear canal. However, the current result is contrasted with an earlier report using a professional golfer to hit three balls with six thin faced titanium drivers,[4] which demonstrated a significantly high noise level in the region of 120-130 dBA, although only a few balls were hit at these intensities in the present study.

Such a discrepancy is mainly due to different measurement methods employed between the study carried out by Buchanan et al. and the present study. Real ear measurement (REM) used in the present study is a common method for measuring SPL near the tympanic membrane.[15] It offers an accurate and objective approach including the individual's real ear acoustic characteristics. By contrast, in the study by Buchanan et al.,[4] the SPL was measured using a sound level meter (SLM) in the free field equidistant from the golfer. The limitation of this measurement is not accurate because the acoustical effects of the ear canal resonance are not taken into account. Moreover, the other key issue is that the SPLs measured in the free field are not the actual SPLs in the ear canal because the baffle effect of head and torso is also important for measuring sound transfer from the free field to the ear. In addition, the skills and power possessed by professional golfers may play a role in generating louder SPLs than is the case for amateur golfers.

Although various studies have suggested that exposure to stimuli exceeding the 100% daily noise dose would cause hearing damage, including a hearing sensitivity reduction, tinnitus, hyperacusis and distortion,[5,6,16] recent research argued the appropriateness of applying industrial risk criteria with recreational noise exposure, because these standards were developed specifically for spectrally dense industrial noise with limited dynamic range as an exposure dose for an 8 hour workday. Therefore, comparisons with industrial standards have to be made with caution. Nevertheless, according to the intensity and noise exposure dose calculation found in the present study, the risks are, on the whole, negligible, i.e., the golf players, particularly amateur players are most unlikely to have hearing damage. However, it is noteworthy that some golf clubs can generate extremely high levels of noise, such as at the maximum value of 123dBA recorded from Club 1 used in the study. With such high noise intensity exposure, it is most likely to pose a significant risk of noise induced hearing loss if the driver is used frequently. This would fit with the case study of an amateur golfer presenting with sigificant hearing loss.[4]

Furthermore, the sound of a golf club hitting a golf ball is one of the influencing factors at a subconscious level on a golfer's perception of quality and his/her choice of equipment, because it provides information on whether the ball was hit correctly. Therefore, golf club manufactures tend to make new models of golf driver clubs using various materials (such as titanium) not only to achieve longer distances, but also to create unique sound characteristics to attract attention. The study by Roberts et al.[17] investigated the relationship between the impact sound and elite golfers' subjective perceptions of a shot. They found a strong relationship between the characteristics of sharpness and loudness of sound, and pleasantness and liveliness of perception. Significantly positive correlations were also obtained between the subjective ratings and parameters of the impact sound such as sound pressure level, loudness level and sharpness. This suggests that the golfers' perceptions are influenced by frequency components, loudness and duration.

In addition, the FFT analysis in the previous study [13] showed different sounds in terms of frequency characteristics and reverberation of the tonal components generated by different clubs when they hit the balls. This is in keeping with the findings of the present study, demonstrating that the peak frequency characteristics recorded from golf driver clubs varied significantly between 2.5 and 3.5 kHz. This is associated with the design (e.g., the structure of the club head) and materials used to make these modern clubs, which have been created by the manufactures in order to achieve a more balanced frequency distribution and thus a better sound quality. However, with such clubs, they are likely to create louder hitting sounds than conventional golf clubs, which potentially causes damage to golfers' hearing.

In the present study, the results did not show evidence of a head shadow effect ~~in that~~insofar as there was no~~t a~~ significant difference in sound ~~intensities~~intensity between the recordings from the near and far ears. ~~It has been~~There is some controversy ~~on~~about asymmetrical noise exposure even though both ears are exposed directly to impact sound sources. (8,18,19,20) Some previous studies argued that left ear noise-induced hearing losses are predominantly common in the army~~. It is explained that~~, because the ear opposite to the dominant hand sustains over~~ly~~ ~~exposed~~exposure mainly due to the shooting posture. [18,19] However, a recent study ~~This is consistent with some previous studies~~ on hearing performance ~~between ears~~ after recreational firearm use ~~in participants in the army having no asymmetrical shooting posture.[18] Although several early studies found that the ear opposite to the dominant hand sustained a more pronounced hearing loss, a recent research study~~ did not reveal a significant preference in terms of temporary threshold shift between ears, irrespective of the dominant hand~~ after recreational firearm use~~.[8] The other study by Job et al. [20] showed that the asymmetry of hearing thresholds between the left ear and right ear was not associated with the subject's shooting posture. They suggested that it is most likely due to different intrinsic characteristics in each side of the ears. In addition, no head diffraction effect found in this study can be explained as rapid movement of the torso and the head when swinging the golf club, which means that exposure to the impact noise generated is spread across the two ears. When the torso is uncoiling, the body and head move to a position where both ears face directly into the impact sound sources. Therefore, one side of the ear is overly exposed, and as a consequence, a unilateral hearing loss is unlikely to be developed from playing golf.

Swing speed did not show any significant correlations with either acoustical characteristics measured in the golf driver clubs (i.e., intensity levels and peak frequencies). Golfers' skill and power (particularly among professional golfers) may be one of the important influencing factors on swing speed. ~~In addition, i~~It is noteworthy that another important factor is the area of the club face hitting the ball to ~~make~~ create an impact because the face of the driver club has a 'sweet spot' where the trampoline effect is optimal. The trampoline effect refers to a pronounced deformation of the club face upon impact followed by a quick restoration to its original dimensions, acting like a slingshot. When the club face hits the ball right on the sweet spot, it results in very high ball speeds. In the present study, it is impossible for the participants to control this factor ~~for delivering~~in order to deliver the same performance ~~by~~with each strike. An investigation of strikes out of the heel, toe and sweet spot using an automated and controlled swing motion with a robot [~~19~~21] would add valuable insight into this enquiry, particularly when comparisons are made between amateur and professional golfers.

CONCLUSION

Different clubs generated significantly different real ear acoustical characteristics in terms of sound pressure levels and frequency responses. On the basis of the SPLs measured in the present study, the immediate danger of noise induced hearing loss for amateur golfers is quite unlikely. However, it is most likely to pose a significant risk of noise induced hearing loss if the driver generates high noise intensity greater than 116 dBA. Provision of detailed information on a club's acoustical characteristics may help consumers choose the appropriate device for their needs, particularly for people who are prone to hearing damage. A longitudinal study monitoring hearing thresholds would provide a valuable insight in terms of the long-term risks to hearing.

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COMPETING INTERESTS

There are no competing interests.

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DATA SHARING

Additional data is available by contacting authors.

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CAPTIONS OF FIGURES

Figure 1 Diagram of experimental settings and equipment used

Figure 2 Scatter plot of averaged sound pressure levels (SPLs) obtained in individuals in the far and near ears generated by three golf drivers.

Figure 3 Scatter plot of averaged frequency responses obtained in individuals in the far and near ears generated by three golf drivers.

Figure 4 Percentage of daily noise exposure when hitting golf balls using the drivers

Figure legend:

Arrow label (→): The percentage of daily noise exposure per basket (40 golf balls)

Figure 1

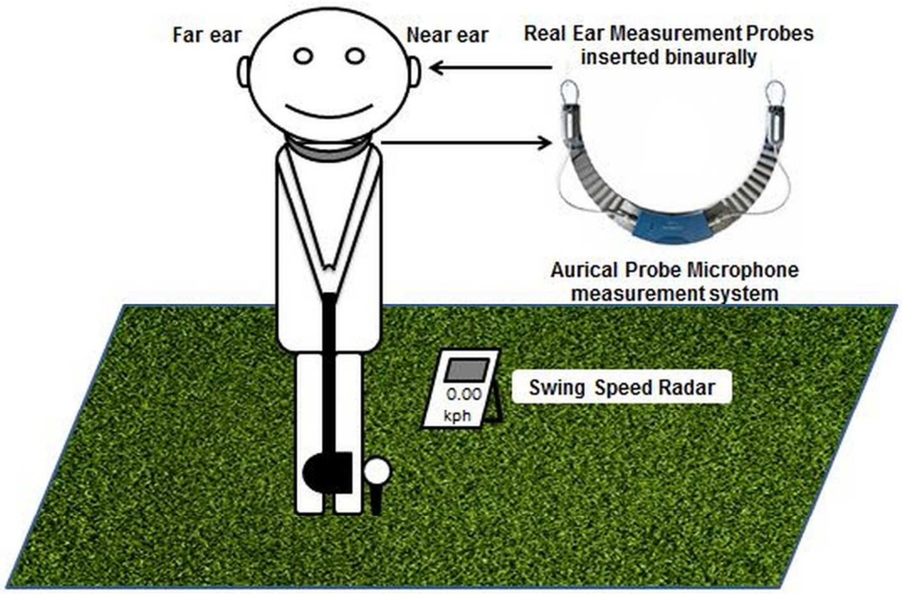

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Figure 2

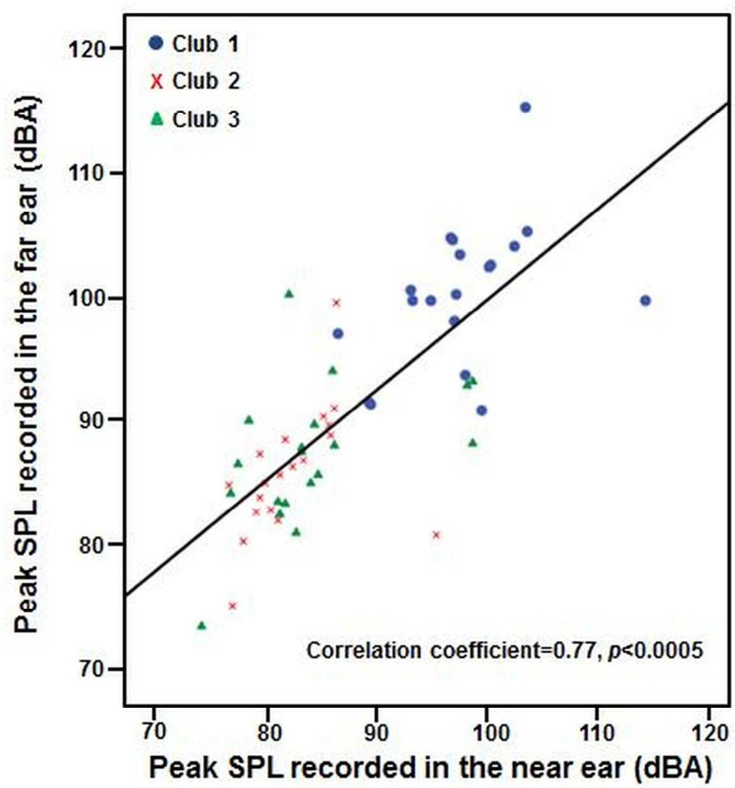

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Figure 3

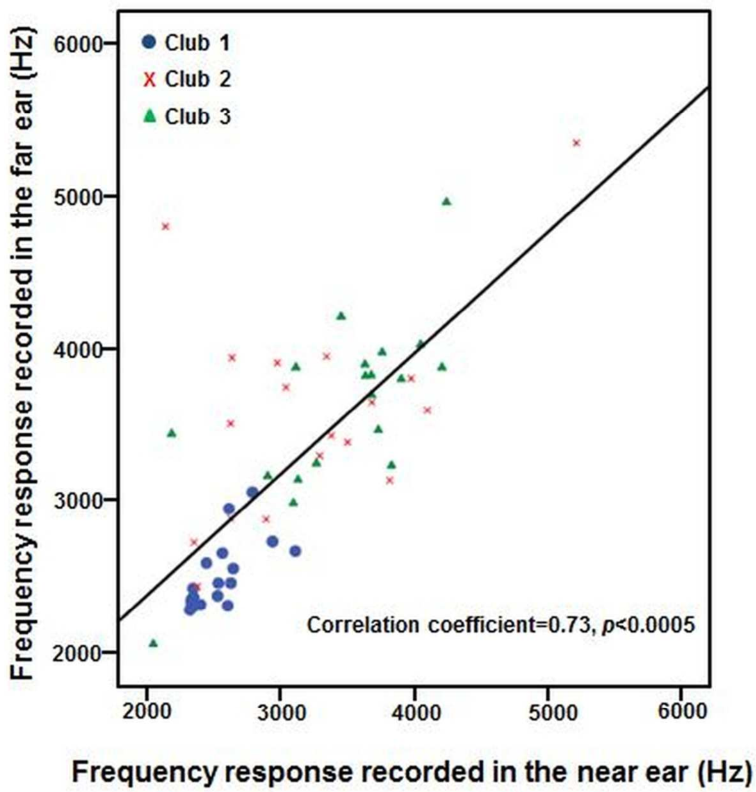

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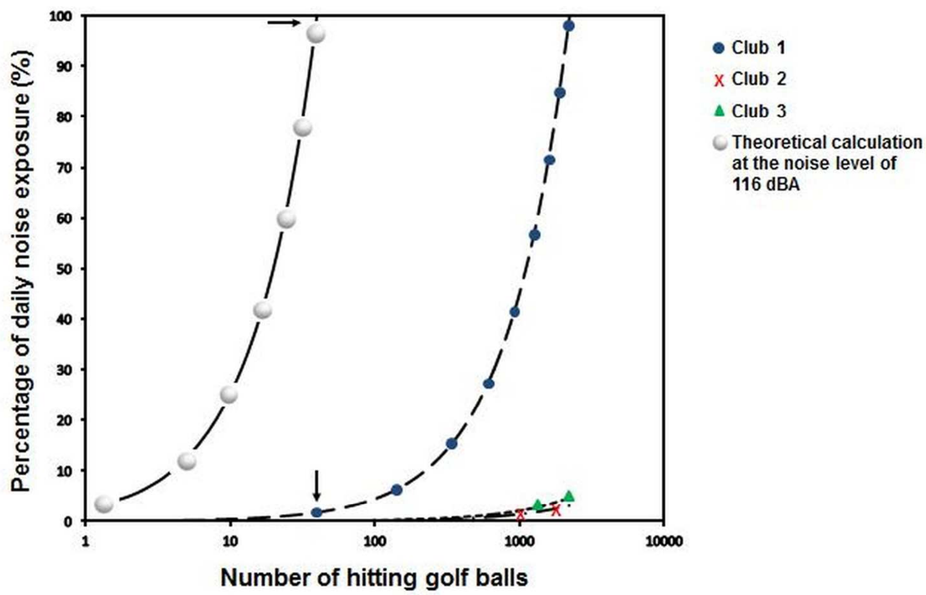
Figure 4



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