Exhibit 16

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FULL-LENGTH ORIGINAL RESEARCH

Potential of wind turbines to elicit seizures under various meteorological conditions

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Summary

Purpose: To determine the potential risk of epileptic seizures from wind turbine shadow flicker under various meteorologic conditions.

Methods: We extend a previous model to include attenuation of sunlight by the atmosphere using the libradtran radiative transfer code.

Results: Under conditions in which observers look toward the horizon with their eyes open we find that there is risk when the observer is closer than 1.2 times the total turbine height when on land, and 2.8 times the total turbine height in marine environments, the risk limited by the size of the image of the sun's disc on the retina. When looking at the ground, where the shadow of the blade is cast, observers are at risk only when at a distance <36 times the blade width, the risk limited by image contrast. If the observer views the horizon and closes their eyes, however, the stimulus size and contrast ratio are epileptogenic for solar elevation angles down to approximately 5°.

Discussion: Large turbines rotate at a rate below that at which the flicker is likely to present a risk, although there is a risk from smaller turbines that interrupt sunlight more than three times per second. For the scenarios considered, we find the risk is negligible at a distance more than about nine times the maximum height reached by the turbine blade, a distance similar to that in guidance from the United Kingdom planning authorities.

KEY WORDS: Photosensitive epilepsy, Flicker, Wind turbines, Atmospheric scattering of light.

The shadow from the blades of certain wind turbines can result in changes in retinal illumination at a rate >3 Hz. Flicker at such frequencies is known to cause epileptic seizures in susceptible people (Binnie et al., 2002). The risk is known to depend upon (1) the flicker frequency; (2) whether one or both eyes are stimulated; (3) the area of the retina receiving stimulation; (4) whether the central or peripheral retina is stimulated; (5) the amount of the change in light intensity (modulation depth); (6) the nature of its variation over time (mark/space fraction); and (7) the spectral composition of the light. A simple model that takes into account these parameters has been published (Harding et al., 2008), but the model fails to consider the atmospheric effects that reduce the shadow contrast. In the following article, we extend the earlier model of Harding et al. to include estimation of the effects of atmospheric scattering. The current view used by United Kingdom planning authorities is simply that "Flicker effects have been proven to occur only within ten rotor diameters of a turbine" (Office of the Deputy Prime Minister, 2004). Therefore, if the turbine has 80-m diameter blades, the potential shadow flicker effect could be felt up to 800 m from a turbine.

The depth or darkness of the shadow of a turbine blade will depend on how much of the light comes directly from the sun and how much comes from elsewhere in the sky as a result of diffuse radiation. This in turn depends on the solar elevation (itself a function of latitude, time of day, and season), and on the amount of aerosols and optically thin clouds in the atmosphere. If the optical depth of cloud is sufficient to completely block the direct beam, then there is no shadow. The greatest contrast will be found when the atmosphere is clean and cloud free, when the scattering that leads to diffuse radiation is strongly wavelength dependent.

Although there is a little evidence that long wavelengths may be more epileptogenic (Parra et al., 2007), the basis for this is currently uncertain, and insufficient to suggest an action spectrum different from that for photopic vision. The variation in photopic luminance (V_λ) will, therefore, be considered.

Method

To determine the risk of seizures from wind turbines in persons with photosensitive epilepsy we have modeled the light–dark contrasts of turbine shadows for worst case

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conditions, that is, for a completely cloud-free atmosphere with the turbine blades rotating in a vertical plane and directly facing the observer on a line between the observer and the position of the sun in the sky. The observer is assumed to be looking straight ahead, so that we consider the radiation falling on a vertical plane at the location of the observer's eye (Fig. 1). We consider the mark/space fraction of the flicker to be within the epileptogenic range for reasons outlined by Harding et al. (2008).

For each meteorologic case, a determination of the diffuse radiance distribution in the sky, the intensity of the direct beam, together with the surface reflectivity (albedo) is required. To this end the libradtran radiative transfer code has been used (Mayer & Kylling, 2005). The model has been developed over several years and verified in a variety of measurement campaigns and, therefore, can be considered robust and reliable.

In the first instance we model the solar radiation for four possible atmospheric and ground conditions: a marine aerosol with a visibility of 30 km over a water surface, a rural aerosol also with a visibility of 30 km, an urban aerosol with a visibility of 10 km, and haze with a visibility of only 5 km. For all the nonmarine model runs, a grass surface was assumed. Although many of the larger turbines are located in open areas, the smaller turbines that have a higher and more epileptogenic flicker frequency are often located on roof tops. Roof surfaces exhibit a range of albedos; for simplicity we take the combined effect to be broadly similar to that of grass. The aerosol characteristics were taken from Shettle (1989) and the albedo for grass from Feister and Grewe (1995). The equivalent value for water, however,

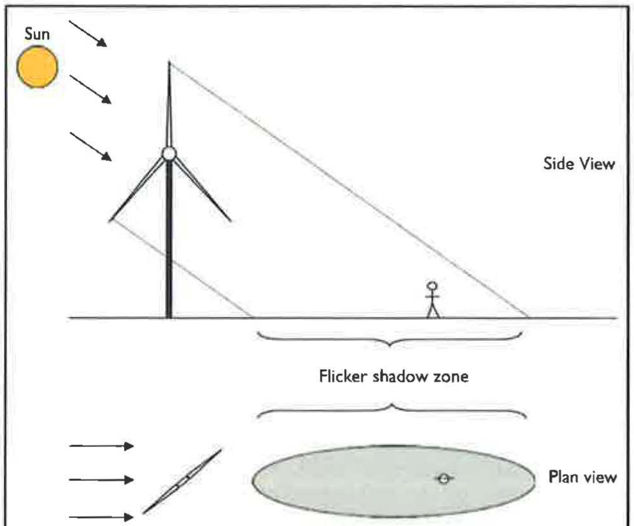

Figure 1.
Generalized geometry for turbine flicker, showing an observer in the shadow area. Note the main analysis assumes the observer and turbine blades are directly facing each other.
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was simply set at 0.035, due to the complications inherent in assigning a single Lambertian value for the range of sea states that could occur.

In many environments, especially urban areas, the presence of buildings, trees, and other obstructions close to the observer, as well as clouds close to the horizon, prevents the sun being viewed close to the horizon. Therefore, the lowest solar elevation angle modeled was chosen as 2°. Similarly for an observer looking directly ahead, once the sun is out of their field of view, the primary stimulus no longer has any potential to cause epileptic seizures; consequently, the upper limit is chosen as 40°. The model has been run at intervals between these two limits.

The output radiance distributions, calculated for wavelengths of 380–760 nm at 10 nm intervals, have been weighted with the CIE 1924 photopic action spectrum (Wyszecki & Stiles, 1982) to represent the sunlight as detected by the human eye. These values have then been converted to irradiances incident on a vertical surface, representing the observer's eye.

To incorporate the effect of a turbine blade upon these received irradiances, we make the assumption that the radiance in the vicinity of the solar disc is rotationally symmetric; this simplifies subsequent analysis, as only the angular width of the blade need be considered, with the relative position of the turbine axis with respect to the sun being removed. The contrast function then results from the blade obscuring the sky and occasionally the sun behind it.

Still considering the observer to be looking toward the horizon with the turbine in the foreground, we also include the cortical magnification factor (Drasdo, 1977)—an expression of the relative density of neurons on the visual cortex and hence the relative contributions of each part of the stimulus—to determine the perceived relative intensities of the direct and diffuse contributions (see Harding et al., 2008).

Then to find the contrast ratio, that is, the extremum value of the time varying contrast function, we additionally consider the area of the sun's disc that is obscured by a blade. As the observer becomes more distant from the turbine blade, the blade will obscure a smaller fraction of the direct beam/sun's disc. At a certain distance the fraction of the direct beam obscured as each blade passes in front of the sun will decrease to the point that the contrast is insufficient to induce seizures. The threshold Michelson contrast has been estimated as 5–10%, depending on the dataset used (Harding & Fylan, 1999; or Wilkins et al., 1980), which equates to a Weber contrast of 10–18%. In this case we define contrast in terms of the Weber fraction, as appropriate when the mark/space ratio is low, and we choose the more risk-averse figure of 10%. This contrast threshold distance is defined by the area of the sun obscured by the blade (the threshold obscuration area) and is, therefore, a function of the relative contributions of the diffuse and direct components and, in turn, the state of the atmosphere and the solar elevation.

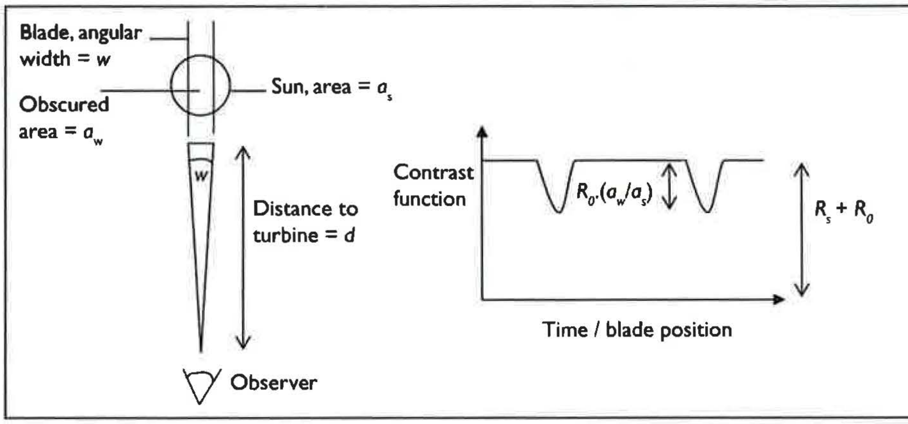

Figure 2.
Geometry showing symbols used in calculation of threshold distance.
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To calculate the threshold obscuration area, we set the reduction in direct beam intensity due to blade obscuration equal to the maximum intensity multiplied by the epileptogenic contrast threshold (see Fig. 2 for geometry). The maximum intensity occurs when the sun is unobscured, and is given by the sum of the direct and sky contributions. The intensity is reduced most when the blade lies symmetrically over the sun, obscuring a fraction a_w/a_s of the direct beam, where a_w is the threshold obscuration area and a_s is the area of the solar disc. Rearranging, the threshold area can then be expressed as follows:

$$a_w = \frac{a_s(R_s + R_0)\,C_w}{R_0}$$

Here C_w is the epileptogenic contrast threshold, R_s is the relative contribution from the sky, and R_0 is the relative contribution of the sun's direct beam.

The blade is assumed to be delimited by parallel edges in the region of interest and lying symmetrically over the sun's disc at the time of minimum contrast ratio. Simple geometry then enables the threshold area to be expressed as an angular blade width.

Finally, the threshold width in each meteorologic situation can be converted to find the threshold distance in units of blade width—this is the distance beyond which the flicker from the turbine blade is no longer epileptogenic to an observer because the contrast ratio would fall below 10%. It is, as follows:

$$d = 0.5\cot(w/2),$$

where w is the threshold angular blade width.

Results and Discussion

As the aerosol loading of the atmosphere and the solar elevation angle change, the relative contributions of the diffuse and direct components will alter. In turn, as turbine blades pass in front of the sun, the fraction of the solar disc that results in a threshold contrast ratio will vary. When applying the analysis in the preceding section to the cases modeled, we obtain the distances at which this threshold is reached. These are shown in Fig. 3.

It is clear that as the amount of aerosol in the atmosphere decreases, the direct beam contribution rises and so the threshold distance increases. Furthermore, when the sun approaches the horizon for the high visibility (low aerosol) cases the threshold distance increases to over 1,000 times the blade width. From atmospheric radiative considerations alone for each level of aerosol loading, it would be expected that as the solar elevation angle increases, a corresponding increase in the threshold distance would also be seen. However, the direct beam contribution in fact decreases with increasing solar elevation angle due to the cortical magnification factor. It is competition between these two aspects that results in a peak at 15–20° for the two highest aerosol cases and at 5° for the low aerosol cases: At lower solar elevation angles the direct beam is reduced by aerosol interactions, and at higher elevations its contribution falls due to the decreasing cortical magnification factor. Furthermore, it can be seen that the differing albedos of grass and

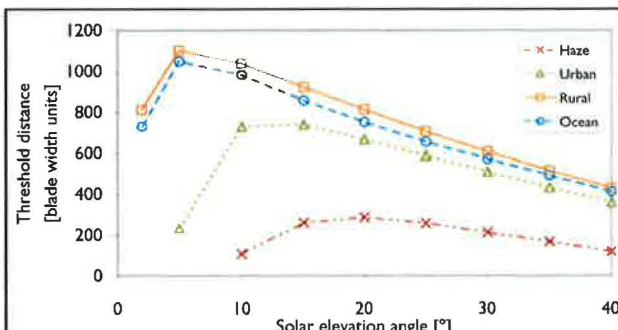

Figure 3.
Threshold distances corresponding to a threshold contrast ratio of 10%, as a function of solar elevation angle for sample aerosol loadings, as described in the text.
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water and the different aerosol properties in the two cases, increase the observed diffuse radiation component for marine environments, and in turn the threshold distances. It will also be noted that there is a lower limit reached for high aerosols—where even when the blade obscures the entire sun the contrast threshold is not achieved.

Taking the maximum threshold distance allows two example turbines to be considered. Wind turbines are commonly either for large-scale power generation as standalone structures, or for microgeneration, being sited on or close to the structure requiring electricity. A typical large 2MW turbine has a blade width of approximately 2 m (although very close to the rotation axis it may be more than this, and will taper toward the point). The contrast ratio threshold distance for a clear, low aerosol day would then be ~2 km. For a small turbine the equivalent distance is an order of magnitude less at 200 m, assuming a blade width of 20 cm.

It should be noted, however, that this does not imply that there is a risk of seizures wherever the turbine can be seen. For there to be a risk, the observer still must be within the shadow zone. For the 2MW turbine example (total height of 120 m), the furthest part of the shadow falls 1,380 m from the turbine when the sun is 5° above the horizon—less than the threshold distance in the previous paragraph. Therefore, in this example the locations on the ground that present a risk of seizures are determined by the extent of the shadow and not the contrast ratio threshold. This point suggests that there are a number of other factors that ought to be considered. We will discuss these below.

The most pertinent is a direct consideration of the cortical magnification factor. From Drasdo (1977) and Binnie et al. (2002), the proportion of patients at risk from a stimulus subtending a half-angle ϕ can be given as follows:

$$p = -0.184 + 2.1(1 - \exp(-0.0574\phi))$$

Solving for p = 0, shows that when the stimulus subtends a half-angle <1.6°, no patients are at risk. In our case the dominant stimulus is the solar disc, which subtends a total angle of 0.53°, implying that although the contrast ratio would appear to be sufficient to cause seizures, the size of the solar disc stimulus prevents the flicker from being epileptogenic.

Yet the analysis thus far only includes radiative transfer in the atmosphere. A further consideration is scattering of the external stimulus within the eye, before the image reaches the retina. Following Vos et al. (1976), the intensity profile of an external point source falling on the fovea can be expressed as a power law for angles >1′. In general 50% of the source intensity falls within 2′ and 3′, and 90% within 1°.

We take the edge of the sun's image to be the radius at which the solar entopic stray light is 10% of the steady diffuse background, the same limit used by de Wit and Coppens (2003). (Entopic scatter of the circumsolar radiation itself has not been included, although it is noted it would increase the calculated values slightly—the direct beam contribution will always be much larger.) To determine this radius, the ratio of the direct beam irradiance to the circumsolar value was calculated and multiplied by 0.1. The apparent radius of the solar disc was then found from the tables provided in Vos et al. (1976). This is plotted in Fig. 4, alongside the epileptogenic threshold radius of 1.6°. It is clear that for most combinations of solar elevation angle and aerosol loading, the minimum epileptogenic stimulus size is not reached. Moreover, even with the lowest aerosol loadings this threshold is not reached when the sun is <20° above the horizon. For land-based turbines the equivalent solar elevation angle is 40°—the upper limit of our analysis. The implications of this result are as follows: considering the contrast ratio threshold alone would lead to the conclusion that wind turbines can cause seizures up to 2 km distant; including the apparent stimulus size limits the solar elevation angle to 40° on land, and hence the maximum "at risk" distance is reduced to 1.2 times (cot 40°) the total turbine height (hub height plus blade length). For marine environments the "at risk" distance is 2.8 (cot 20°) times the total turbine height. In each case the total turbine height includes the height of any structure that the turbine might be situated on, for example, a building.

The weather conditions modeled so far have neglected the presence of clouds or other nonhorizontally homogenous components. The minimum stimulus size required for patients to be "at risk," however, allows us to consider a more general meteorologic situation with a bright patch in the sky of angular width 1.6°. Assuming the other epileptogenic conditions are met, this defines an angular blade width that would be required to cover and uncover the stimulus. The threshold distance in this case is equal to 35.8 multiples

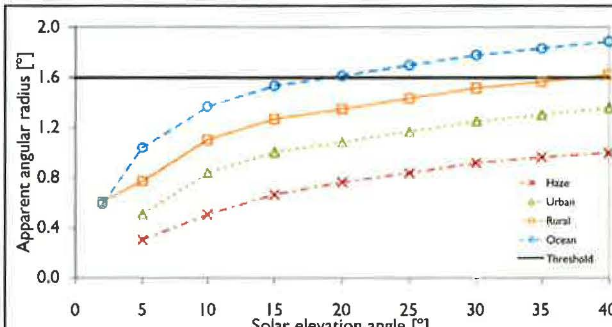

Figure 4.
Apparent solar angular radius due to entopic (intraocular) scattering. The perceived edge is defined as the radius from the center of the retinal image of the sun at which intraocular scattering has reduced the sun's image intensity to 10% of the diffuse background intensity.
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of the blade width. For the large turbine example this would be approximately 70 m from the blades, and for a small turbine, approximately 7 m.

Up until this point we have assumed that the observer is directly facing the turbine looking toward the horizon. This would seem to be a reasonable first assumption; it also simplified calculations and caused the sun to be within the observer's field of view. That said, except during high aerosol loadings of the atmosphere, it is the body's natural response to look away from the sun, or to partially close the eyelids (Sliney, 2005). Indeed it is widely recommended not to view the sun directly because of the risk of retinal damage. Without the solar disc in the observer's field of view though, the analysis described in the preceding text does not hold.

There are some other possible scenarios in which turbine flicker of the direct solar beam could be epileptogenic. First where the observer stands in the shadow zone, but views the ground, and second, an observer viewing the turbine blades against the sky. The analysis was similar to that for the main case, but the threshold distances were found to be about two orders of magnitude smaller, with a maximum of 36 times the blade diameter for the marine case. The rural, urban, and haze aerosols all had lower threshold distances. This corresponds to a distance at which the general public would normally be excluded on other safety grounds, and may be less than the distance from the blades to the ground.

If rather than looking down, an observer chooses to close their eyes, but remains with their gaze directed ahead, the threshold distance is as in Fig. 5. The effect of the eyelids is to reduce the transmission of the incoming radiation (in the present study this is assumed to be wavelength independent), and to scatter radiation from all directions equally. The diffuse contribution is, therefore, the mean irradiance within a 40° field of view, and does not include any weighting by the cortical magnification factor because the entire retina is then equally stimulated. From Fig. 5 we see that the contrast ratio threshold distance now increases with increasing solar elevation angle. For the lowest aerosol loadings this is from <600 at 5° to almost 1,100 at 40°. As discussed earlier for the main "eyes open" case, the limiting factor for marine and rural aerosols for these solar elevations is then the distance from the turbine that a shadow falls, rather than the contrast ratio threshold distance. For the 2MW turbine example with solar elevations of 5° and lower, we find that the contrast ratio threshold distance is the limiting factor. For example a 120 m total tower height, with blades 2 m wide, the contrast ratio threshold distance at 5° is 1,070 m on land—approximately nine times the total turbine height. The shadow, however, would extend to 1,370 m. As the sun drops lower, the contrast ratio threshold will fall and the blades' shadow will be cast outside this limit, therefore, not creating a risk of seizure. This worst case scenario is in line with the rule of thumb used by United Kingdom planning authorities to determine the "at risk" region—10 times the total turbine height (Harding et al., 2008).

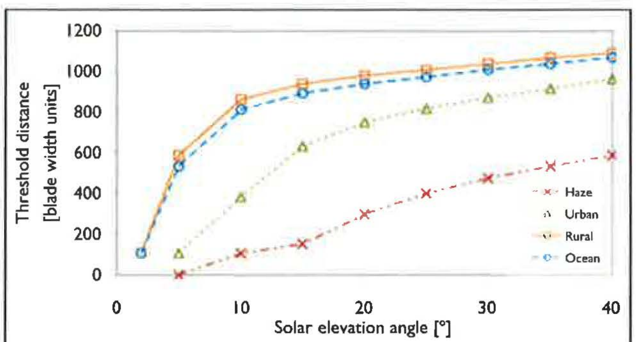

Figure 5.
Threshold distances as a function of solar elevation angle for sample aerosol loadings and an observer with closed eyelids.
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The final contributing aspect to epileptogenic flicker is its frequency. Modern turbines are designed to have a constant tip speed ratio:

$$\lambda = \frac{4\pi}{n},$$

where n is the number of blades. The most efficient three-bladed turbines may have tip speed ratios of 6–7. The frequency at which the blades pass in front of a point on the sky can then be expressed as:

$$\nu = \lambda u \cdot \frac{n}{2\pi l} = \frac{2u}{l},$$

where u is the wind speed, and l is the blade length. This is in accordance with the fact that microgeneration turbines rotate faster than their larger counterparts. However, for the 2MW example, with 40 m blades, a wind speed of 20 m/s is required before the flicker frequency reaches 1 Hz, which is close to the typical storm protection shutdown speed of 25 m/s (BWEA 2005). Turbines of this size, therefore, rotate slower than 3 Hz, the lower frequency threshold at which seizures are a potential risk. For smaller turbines the flicker frequency is expected to be a factor of 10 or more higher, and, therefore, would have the potential to affect a larger proportion of people with epilepsy. For typical mean wind speeds of 5 m/s and a blade length of 2 m, the flicker frequency would be 5 Hz, although helical designs rotate at higher speeds and have shadows that move against one another, increasing the rate of shadow flicker.

Conclusions

This study has used a robust and accurate radiative transfer model to predict the radiance distribution and direct solar beam intensity for a range of clear sky atmospheric conditions. It is found that for a low aerosol loading of the atmosphere the epileptogenic contrast threshold of 10% is met for all locations where the turbine blade shadow would be reasonably expected to fall. However, with the eyes open, the apparent angular radius of the stimulus falls below the limit where any patients would be at risk (1.6°) for solar elevation angles of 40° or less (on land) and 20° or less (marine environments). Therefore, we envisage no epileptogenic risk to observers looking toward the horizon except when standing closer than 1.2 times the total turbine height on land, or situated closer than 2.8 times the total turbine height in marine environments.

Furthermore, considering the tendency of patients to look away from the sun as a natural reaction, but for those who find themselves in the shadow zone, we find that for an observer viewing the ground the contrast is almost always insufficient to be epileptogenic. If, alternatively, the observer maintains their gaze, but closes their eyes, then both the contrast ratio threshold distance and stimulus size conditions are sufficient down to a solar elevation angle of 5°, for the example discussed. In other words, when solar elevation is greater than 5°, there is epileptogenic potential where the blade's shadow falls. Below this angle the contrast ratio threshold limits the "at risk" region to <535 times the blade width on land. For the large turbine example used this corresponds to nine times the total tower height. It is noted that eye closure is a natural immediate protective action when exposed to flicker, and so has the unfortunate consequence of exacerbating its adverse effect in this context. A more effective strategy would be to cover one eye with the palm of a hand as monocular stimulation is known to be generally far less epileptogenic (Harding & Jeavons, 1995), or for the observer to simply avert their gaze toward the ground.

Finally we find that if flicker of sufficient contrast and stimulus size were produced by turbines, the larger turbines are unlikely to rotate fast enough to induce seizures. However, the rotation frequency increases inversely with the blade length, making small microgeneration turbines more likely to induce seizures, should the combined intensity and stimulus size conditions be met.

Acknowledgments

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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