Minimising the impact of biologging devices: Using Computational Fluid Dynamics for optimising tag design and positioning

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Abstract

1. Biologging devices are used ubiquitously across vertebrate taxa in studies of movement and behavioural ecology to record data from organisms without the need for direct observation. Despite the dramatic increase in the sophistication of this technology, progress in reducing the impact of these devices to animals is less obvious, notwithstanding the implications for animal welfare. Existing guidelines focus on tag weight (e.g. the '5% rule'), ignoring aero/hydrodynamic forces in aerial and aquatic organisms, which can be considerable. Designing tags to minimise such impact for animals moving in fluid environments is not trivial, as the impact depends on the position of the tag on the animal, as well as its shape and dimensions.
2. We demonstrate the capabilities of computational fluid dynamics (CFD) modelling to optimize the design and positioning of biologgers on marine animals, using the grey seal (*Halichoerus grypus*) as a model species. Specifically, we investigate the effects of (i) tag form, (ii) tag size and (iii) tag position and quantify the impact under frontal hydrodynamic forces, as encountered by seals swimming at sea.
3. By comparing a conventional vs. a streamlined tag, we show that the former can induce up to 22% larger drag for a swimming seal; to match the drag of the streamlined tag, the conventional tag would have to be reduced in size by 50%. For the conventional tag, the drag induced can differ by up to 11% depending on the position along the seal's body, whereas for the streamlined tag this difference amounts to only 5%.
4. We conclude by showing how the CFD simulation approach can be used to optimise tag design to reduce drag for aerial and aquatic species, including issues such as the impact of lateral currents (unexplored until now). We also provide a step-by-step guide to facilitate implementation of CFD in biologging tag design.

Second Language Abstract (Welsh)

1. Defnyddir dyfeisiau biogofnodi'n eang iawn ar draws dosbarthiadau fertebratiaid mewn astudiaethau symudiad ac ymddygiad ecolegol i gofnodi data o organeddau heb fod angen arsylwi'n uniongyrchol. Er gwaethaf y cynnydd syfrdanol yn natur soffistigedig y dechnoleg hon, mae'r cynnydd wrth leihau effaith y dyfeisiau hyn ar anifeiliaid yn llai amlwg, er gwaethaf y goblygiadau ar gyfer lles anifeiliaid. Mae canllawiau presennol yn canolbwyntio ar bwysau tag (e.e. y 'rheol 5%'), gan anwybyddu grym aero/hydrodynamig mewn organeddau awyr a dyfrol, sy'n gallu bod yn sylweddol. Nid yw dylunio tagiau i leihau effaith o'r fath i anifeiliaid sy'n symud mewn amgylcheddau llifyddol yn beth bach, gan fod yr effaith yn dibynnu ar leoliad y tag ar yr anifail, yn ogystal â'r siâp a'i ddimensiynau.
2. Rydym yn dangos galluoedd modelu deinameg hylif gyfrifiannol (CFD) i optimeiddio dyluniad a lleoliad biogofnodwyr ar anifeiliaid morol, gan ddefnyddio'r morlo llwyd (*Halichoerus grypus*) fel rhywogaeth fodel. Yn benodol, rydym yn ymchwilio i effeithiau (i) ffurf y tag, (ii) maint y tag a (iii) lleoliad y tag a meintoli'r effaith dan rymoedd hydrodynameg uniongyrchol, fel y mae morloi sy'n nofio yn y môr yn eu profi.
3. Drwy gymharu tag confensiynol â thag llyfn, rydym yn dangos y gall y fersiwn gonfensiynol greu hyd at 22% mwy o effaith lusgo i forlo sy'n nofio; er mwyn efelychu effaith lusgo'r tag llyfn, byddai'n rhaid lleihau maint y tag confensiynol gan 50%. Ar gyfer y tag confensiynol, gall yr effaith lusgo a grëir amrywio hyd at 11%, gan ddibynnu ar ei leoliad ar gorff y morlo, er mai 5% yn unig yw'r gwahaniaeth hwn ar gyfer tag llyfn.
4. Rydym yn cloi wrth ddangos sut gall ymagwedd efelychu CFD gael ei defnyddio i optimeiddio dyluniad tagiau a lleihau'r effaith lusgo i rywogaethau awyr a dyfrol, gan gynnwys materion megis effaith cerrynt ystlysol (nad ydynt wedi'u hastudio hyd yma).

Rydym hefyd yn cynnig canllaw cam wrth gam i hwyluso rhoi CFD ar waith wrth ddylunio tagiau biogofnodi.

Keywords: animal welfare, biologging, biotelemetry, computational fluid dynamics, drag, flow simulation, hydrodynamics, tag design

1 Introduction

In recent decades, the use of biologging devices to gather information on the behaviour, movement and physiology of animals has increased substantially (Hussey et al. 2015). In addition to collecting vast amounts of movement and behavioural data (Heylen & Nachtsheim 2018), biologging devices can collect oceanographic data (Roquet et al. 2017; Treasure et al. 2017), and other environmental measures, such as ambient noise levels (Mikkelsen et al. 2019). However, attachment of devices to animals is not without consequence for the animals carrying them (Thorstad et al. 2001; Vandenabeele et al. 2014; Bodey et al. 2017; Wilson et al. 2018). Tag-induced detriment has often been attributed to tag weight (Kenward 2001) which has driven researchers to work within weight-defined bounds (Casper 2009). Indeed, researchers often select their study animals based on the size or weight requirements for the tags, rather than trying to optimise tags for a given species or size class; though there are examples of specific developments made for very small animals (Stidsholt et al. 2018). Despite this, most studies using tags have so far largely failed to take advantage of technological advancements to reduce the impact of tags on animals (Portugal & White 2018). Crucially, for projects involving tags on aerial and aquatic animals, the focus on weight by most existing tag guidelines – e.g. the 3% or 5% rule (Casper 2009) – ignores aero/hydrodynamic impacts (most notably drag) which are key in modulating energy expenditure and behaviour during swimming (Culik & Wilson 1991; Cornick et al. 2006;

Rosen et al. 2017; van der Hoop et al. 2018), and flight (Bowlin et al. 2010; Pennycuick et al. 2012; but see Tomotani et al. 2019). This may lead to biased data which is not representative of freely moving animals (Ropert-Coudert et al. 2000; Barron et al. 2010; Lear et al. 2018), as well as raising important ethical concerns for the animal being tagged (Wilson & McMahon 2006).

Designing minimal-impact tags and testing drag in real systems is however not trivial, as the impact is a complex function of both the position of the tag on the animal as well as its shape and dimensions (Bannasch et al. 1994; Vandenabeele et al. 2015). One approach to assess the effects of tag-induced drag is by *in-situ* modification of the shape and positioning of tags deployed on a subject animal (or a model of it) in wind or flume tunnels, or in captivity (Culik et al. 1994; van der Hoop et al. 2014; Shorter et al. 2017). These approaches are beneficial insofar as during live experiments it is possible to observe how animals react to tags under real operational conditions (cf. Pavlov & Rashad 2012; van der Hoop et al. 2018), as well as assessing animal energetics, kinetics and biomechanics, and changes in these over time (Geertsen et al. 2004; Ropert-Coudert et al. 2007; Rosen et al. 2017; van der Hoop et al. 2018). However, experimental approaches are limited in that they are very time consuming and labour intensive, wind or flume tunnels are not always accessible, and the use of live animals raises ethical concerns and requires appropriate licensing (Kyte et al. 2018). Furthermore, the logistical constraints of working with very large taxa (e.g. cetaceans) often make *in-situ* experiments impractical.

An alternative to experimental approaches uses computational fluid dynamics (CFD) to assess tag-induced drag (Kyte et al. 2018). CFD is the primary tool for virtual design and drag modelling within the aerospace industry (Jameson & Vassberg 2001) and is notable in being able to model drag with the accuracy of results comparable to physical experiments (Tyagi & Sen 2006; Jagadeesh et al. 2009; Vassberg et al. 2014); for example Shorter et al. (2014) demonstrated that CFD simulation predictions of tag-induced drag agreed with experimental assessments. Of particular value is that CFD analysis can be implemented quickly and efficiently and can gather repeated, comprehensive measures on aero/hydrodynamic aspects of tag design. As such, CFD analysis can aid the prototyping of biologging tags prior to manufacture by estimating their effects in a virtual environment without the need for experiments (Pavlov et al. 2007; Kyte et al. 2018). Indeed, CFD has the potential to revolutionise biologging tag design (Heylen & Nachtsheim 2018).

The use of CFD to examine tag design and impact has grown within the biologging community since the mid-2000s (Pavlov et al. 2007) (see appendix S1 for a brief review). Some commercial tag manufacturers utilise CFD to assess tags during product development, though results from these studies are often not published. Indeed, the use of CFD to examine tag-induced drag remains relatively limited in peer-reviewed literature, and its full potential may not yet have been realised. Specifically, while there have been several advances in the use of CFD to design tags and quantify their impact (appendix S1), no publication has yet examined an approach which simultaneously considers device size (Vandenabeele et al. 2015), shape (Shorter et al., 2014) and positioning along the animal’s body (Bannasch et al. 1994; Vandenabeele et al. 2014).

It is important to note that while the use of CFD to assess tag-induced drag is an increasingly popular method, with clear advantages over experimental alternatives (Kyte et al. 2018), it does have limitations, and one of our aims is to help ecologists become aware of these and efficiently deal with them. Briefly, CFD analysis can be sensitive to the choice of turbulence model; results may be specific to the particular tag and animal geometries used in the study (thus care is required to compare results from different studies); and geometric simplifications (such as the removal of antenna) are often required during modelling, which will affect results. Further details of these limitations are covered in appendix S2.

Nevertheless, provided potential limitations are acknowledged, CFD is an excellent tool to test hypotheses at the level of concept (Pavlov & Rashad 2012), particularly if the aim is, as is often the case (including in this study), to compare the drag of tagged versus untagged animals, and to assess the effect of various designs, sizes and positions of tags. CFD software is freely available for researchers, but its use has been largely restricted to commercial tag manufacturers, individuals with substantial prior expertise, or teams who are able to collaborate with aerospace engineers (Kyte et al. 2018). Conversely, novice CFD users, like many ecologists, are not routinely able to implement such techniques themselves.

Here we address this gap and support ecologists to realise the full potential of CFD for improving tag design and assessing tag-induced drag. Specifically, we (i) evaluate how tag-induced drag varies with device shape, size and positioning on the animal, (ii) exemplify the efficacy of CFD for tag design, and (iii) provide step-by-step instructions for ecologists to use CFD to efficiently assess the drag impact of biologging tags (appendix S3); facilitating effective, future interdisciplinary collaborations with engineers.

2 Materials and Methods

In addition to this section, we provide a step-by-step guide to modelling the drag impact of tags with CFD simulations using ANSYS FLUENT™, version R15.0 (ANSYS, Inc., Pennsylvania, USA) (appendix S3).

2.1 Construction of geometries

We used computer aided design (CAD) software (Autodesk® Inventor LT™, Autodesk Inc., California, USA) to construct and manipulate seal and tag geometries. Note that any modern 3D CAD software package will allow the geometric manipulations necessary to reproduce this work. For the purpose of this study, two tag geometries were considered. The first represented a traditional GPS tag for seals (tag A), as used in Hazekamp et al. (2010), measuring 10 x 7 x 4 cm (length x width x height). The second geometry represented a streamlined tag designed by us (tag B), measuring 11 x 10 x 4 cm. Both tags were designed to contain multiple biologging sensors capable of recording data on seal movements and behaviour.

The seal geometry was obtained from Hazekamp et al. (2010) in IGES (.igs) format and converted into a solid body for integration with the tag geometries. We chose to use the seal and tag A geometries from Hazekamp et al. (2010) in order to facilitate direct comparison of results. Importantly, the results from CFD simulations (see later) will depend on (and be specific to) the chosen size of the animal geometry, hence the geometry should be an appropriate reflection of the real animal being studied. Our seal geometry was 1734 mm long – within the range of a typical adult female grey seal (McLaren 1993). Our main aim was to exemplify the CFD method by assessing effects of size, shape and position of the main body design of two tags on induced drag. Hence, to maintain simplicity in the CFD modelling (cf. Kyte et al. 2018), external features such as the antennae were removed from both tag geometries (see appendices S2 and S4 for details).

To prepare the geometries ahead of export to the CFD mesh generation process, we used CAD ‘cleaning’ software (CADfix, International TechneGroup, Inc., Ohio, USA) to ensure that the combined seal-tag solid body was ‘watertight’. This is necessary to allow the subsequent modelling of drag effects of the tag at different positions along the animal’s body.

2.2 CFD simulations

We undertook mesh generation, pre-processing and CFD simulations also within ANSYS Fluent^{TM}. We first undertook a mesh convergence study to determine the appropriate mesh resolutions required for the simulations. We generated a surface mesh (Fig. 1), encompassing the seal body and tag, composed of a finely resolved mesh for the fluid boundary layer around the seal (Fig. 1 (a)), and a further (coarser) volume mesh for the remainder of the volume around the seal body (Fig. 1(b)) (see appendix S4 for further details). The surface mesh provided the input to ANSYS Fluent's numerical solver to simulate the flow and determine flowfield properties, such as turbulence, around the animal body under different freestream conditions, and to compute force coefficient outputs. Importantly, the assumption was made that a steady-state solution existed for each (non-dynamic) case, which allows for local time integration within the CFD solver, as a precise time history of the solution was not necessary.

Flow visualisations were obtained using the software package *EnSight* and ANSYS PostProcessing (ANSYS, Inc., Pennsylvania, USA), to provide a qualitative description of the underlying fluid dynamics causing the force coefficient responses observed. A summary of the CFD process is provided in Fig. 2 (and refer to appendix S4 for specific details; see also appendix S3).

Simulations were undertaken using a range of flow speeds (1, 3, 5, 7 and 9 ms^{-1}) within the typical range for simulation approaches for seals, including resultant speeds encountered when seals swim into an oncoming flow, e.g. in high tidal flow environments (Hazekamp et al. 2010; Kyte et al. 2018; Hastie et al. 2019). We computed non-dimensional force coefficients in order to verify that non-dimensionalised outputs were insensitive to the absolute input freestream velocity across this range; indeed, all force coefficients collapsed onto a single curve across this speed range, indicating that the force coefficient response was independent of freestream speed, and that our results remained consistent across the range of velocities modelled. Thus, a velocity of 5 ms^{-1}

was selected for further investigation because we were particularly interested in the drag effects and performance of tags when flow speed was relatively high; such speeds may be encountered by seals swimming in highly tidal, fast flowing areas (Hastie et al. 2019). In line with Pavlov & Rashad (2012) our model was assumed to represent an animal swimming at a constant speed in a rectilinear fashion. While at sea, seals undertake a range of complex 3D motions (Mitani et al. 2003) and move at varying speeds (Williams 2018). Hence, our results cannot account for the full range of movement that a seal exhibits, but instead focus on the predominant forward motion of straight line swimming that seals undertake during transit (Davis et al. 2001). These simplifications are necessary due to the added complexity of modelling the highly unsteady and interacting effects of fluid flow around a non-rigid, moving body (Adkins & Yan 2006); while these analyses are possible and certainly interesting for future studies, they require the use of unsteady, fluid-structure interaction CFD modelling techniques (Adkins & Yan 2006) and were unnecessary for our aims (see also Kyte et al. 2018).

The output from the CFD simulations was the non-dimensional drag coefficient (C_d) for each seal and tag combination. The Reynolds number, *Re*, of the flow simulations, defined as

$$Re = \frac{\rho V L}{\mu} \qquad (1)$$

where ρ is the fluid density (1028 kg m^{-3}), V is the freestream flow velocity (5 m s^{-1}), L is the seal length (1734 mm) and μ is the dynamic viscosity of salt water (1.09 x 10^{-3} Pa s), was 8.2 x 10^{6}.

All non-dimensional drag coefficients, C_d, defined as

$$C_d = \frac{D}{\frac{1}{2}\rho V^2 A} \qquad (2)$$

where D is the absolute drag value (in Newtons) of each seal and tag combination, were determined for each tag type, at nine discrete positions along the seal's dorsal surface, under frontal flow (zero angle of attack) using the seal frontal area, A (0.134 m^2), as the reference. The nine positions studied ranged from the seal's neck (position 1; 216 mm from the nose) to 1080 mm from the nose (position 9) (Fig. 3). The comparisons of C_d values are for the combined seal-tag body.

2.3 The effect of tag size, shape and position on tag-induced drag

To examine the effect of tag size, we used the non-dimensional drag coefficient (C_d), hereon "drag", obtained from the CFD solver, to predict by how much the standard tag (A) would need to be decreased in size in order to reduce its absolute drag penalty to the same value of the more hydrodynamic tag B (under the same flow conditions). Thus, via a process of linear re-scaling, we iteratively reduced the size of tag A to reach the equivalent drag penalty to that of tag B.

We used a paired t-test to examine the effect of tag shape on tag-induced drag (i.e. mean drag over the full range of nine positions modelled). To test the effect of tag positioning *per se* we modelled drag as a function of position using a linear fixed-effects model (using a cubic polynomial function to account for the non-linear effect of position), including tag type (A or B) as a fixed effect (to account for shape effects), interacting with position. We used step-wise model selection to compare the full model (with an interaction between tag shape and position) vs the intercept only model, as well as comparing cubic vs quadratic polynomial functions for the position covariate, retaining the former in both cases. All analyses were performed using R version 3.5.1 (R Core Team 2018).

3 Results

We used CFD modelling to quantify the drag increase of tags on marine animals over the baseline case of a non-tagged animal, using the grey seal as a model species. The results presented in this section outline the effects of shape, size and positioning of two contrasting tag types on the turbulence and pressures generated around the tag, and hence the drag experienced by tagged animals.

3.1 Turbulence and pressures generated by tags with contrasting shape

Tag A, a standard tag, commonly used for seals and other marine mammals, with a non-streamlined shape, induced considerably more turbulent distortions, particularly in the wake of the device, than the streamlined tag B, with the reattachment point of the lowest, smooth streamline passing over tag A 20% further downstream from the base of the tag than in the case of tag B (Fig. 4). This delayed reattachment of streamlined flow results in a turbulent wake region that is approximately 30% larger (when viewed transversely). This type of drag is often referred to as 'base drag' (Suliman et al. 2009) and is one of the major contributors to the increased drag of tag A. There are also stagnant, turbulent flow regions on the upper side of tag A which are not evident on tag B (Fig. 4). These stagnant regions (due to the less streamlined upper surface of tag A) contribute to increased drag. The peak pressure on the front of tag A is 15% higher than that on tag B and the high pressure region on tag A (see red area in Fig. 4) is 65% larger than that on tag B. There is also evidence of a considerable low pressure (blue) region, generating suction, on the upper surface of tag A which is not present on tag B. The general form of the regions of high and low pressure across the tags was consistent across all positions for both tag shapes (Fig. 4).

3.2 Shape and size effects on drag experienced by tagged animals

Tag A produced an 18.5% greater mean percentage drag increase than tag B across the full range of positions studied ($t = 16.012$, $df = 8$, $p < 0.001$) (Table 1), with a maximum percentage increase of 22.3% greater than tag B (at position 6) (Table 2). These results mean that tag A would require a ca. 50% linear scaling reduction in size to reduce its drag penalty to that of tag B; i.e. from 10 x 7 x 4 cm (c.f. Table 1) to 5 x 3.5 x 2 cm. It is also worth noting that tag B is the preferred option for lower absolute drag despite it being markedly larger than tag A.

3.3 Position effects on drag experienced by tagged animals

The positioning of tags had a marked impact on their drag (Fig. 5) (Tag A: $F_3 = 25.253$, $p < 0.001$; Tag B: $F_3 = 10.362$, $p < 0.001$). Positions 2 and 9 (on the dorsal surface at the neck, and between the shoulder blades respectively; corresponding to 215.75 mm and 1083.44 mm from the tip (nose) of the model), were optimum for tag A and tag B, respectively (Fig. 5). The drag varied non-linearly with positioning, and this effect differed by tag type ($p = 0.002$). Drag was greatest around the mid-point of the dorsal surface on the model seal (specifically, positions 5 and 6 for tag A, and positions 3 and 4 for tag B) (Fig. 5; Table 2). Importantly, the variability in tag-induced drag between attachment positions was markedly greater in tag A, with drag values ranging from 0.071 to 0.078; equating to an increase in drag penalty, compared to a seal with no tag, of +20.8% to +32.1%, with a maximum drag penalty difference of 11.3% between positions 2 and 6. For tag B these values ranged from 0.063 to 0.066, equating to an increase in drag of +6.5% to +11.9%, with a maximum difference of 5.4% between positions 4 and 9 (Table 2). Accordingly, the coefficient of variation in drag for tag A (3.31 %) was almost double that of tag B (1.71 %).

4 Discussion

We showed how CFD modelling can be used to quantify and reduce tag impact on aquatic and aerial animals through virtual design testing. Using the example of tags attached to grey seals, we showed how to evaluate and quantify the interacting effects of tag shape, size and position on the magnitude of tag-induced drag. Our step-by-step guide (appendix S3) provides a standardised framework for ecologists to use CFD to assess the drag impact of tags, and more routinely report it in publications.

Tag A gave rise to a more turbulent flow disturbance, which also propagated over a longer distance, than for tag B (Fig. 4). This contributed to the greater drag generated by tag A (Table 1; 2). This increase in drag can also be attributed to the larger regions of high (red) and low (blue) pressure differentials than for tag B (Fig. 4). This is in accordance with other CFD and wind tunnel research on seals (Kyte et al., 2018), cetaceans (Fiore et al. 2017) and birds (Vandenabeele et al. 2014), where greater turbulent flow distortions and larger pressure differentials contributed to increased drag. We note that the absolute drag values observed in our study are larger than those obtained in Kyte et al. (2018), who modelled tag-induced drag on a similarly sized harp seal. This can be attributed to the large difference in flow velocities used in the simulations; Kyte et al. (2018) used a maximum flow velocity of 1.7 ms^{-1} whereas our simulations used 5 ms^{-1}. Importantly, when scaled to non-dimensional drag, our values are in line with that work. Likewise, when comparing our work to Hazekamp et al. (2010) we found similar yet quantitatively different results. Specifically, Hazekamp et al. (2010) observed a 13.8% increase in drag, whereas we saw an increase of 23.5%. This difference is expected because Hazekamp et al. (2010) ran their simulations using the k-ε turbulence model, which tends to underpredict the drag impact of a tag (see Kyte et al. 2018 and appendix S2 for further details).

Tag A had a considerably larger low pressure region than tag B (Fig. 4) which could negatively impact tagged animals by contributing to a lift force trying to pull the tag off the animal (Fiore et al. 2017). High and low pressure differentials can act to increase shear loading or downforce, which could cause injury at the site of attachment, or lead to early detachment of a tag from an animal (Fiore et al. 2017). Hence, minimising drag will likely also increase attachment time for suction cup tags (Pavlov et al. 2007; Fiore et al. 2017). CFD modelling can also resolve lift forces and we note that both tags generated substantial variation in lift coefficient (C_l) (Table 2), although the magnitude of C_l was negligible compared to the drag. It was not a primary aim of ours to investigate C_l, hence we reserve discussion of this to the supporting information (appendix S5).

Our comparison of two contrasting tag designs allowed us to exemplify that tag shape may be more influential than size *per se* in generating increased drag for tagged animals, with the considerably larger but more hydrodynamically designed tag (B) giving rise to a lower drag penalty than the smaller tag A (Table 1). This result is in agreement with Balmer et al. (2014) who demonstrated that the size of tags was an insignificant driver of overall drag, with only a 1.2% increase in drag between the smallest (25 mm) and largest (38.6 mm) tags studied. Thus, we propose that tag shape should be considered more systematically (Fig 5-6) and we demonstrated how CFD simulations are ideal for this. Moreover, achieving the reduction in size that would be necessary to reduce drag without instead designing a more streamlined form (here a reduction in size of tag A by ca. 50 %) is often not possible due to limitations in the size of electronic components and batteries. On the contrary, our results suggest there may be scope to increase the size of tags, within reason, providing that their form ultimately leads to a reduction in drag (Fig. 6) – see also Shorter et al. (2014) and Fiore et al. (2017). Certainly, seen in this light, the persistent stated aim to simply ”miniaturise” biologging devices may be too simplistic (Portugal & White 2018).

If tag size is to be increased, other factors such as minimizing the area of contact with the animal (i.e. tag footprint) or the method of tag attachment must also be considered (Shorter et al. 2014). This is because the direct attachment of tags to study animals has been shown to disrupt thermoregulatory responses, or create superficial abrasions (McCafferty et al. 2007; Field et al. 2012). For example, tags attached to juvenile grey seals gave rise to a 23% greater heat-flux where devices were attached, compared to areas of undisturbed fur, which was likely due to heat leakage around the attachment site (McCafferty et al. 2007). Superficial abrasions were observed when tags were attached to seals using a mesh attachment (Mazzaro & Dunn 2010), and the use of epoxies to attach external devices to the pelage of animals has the potential to cause burns at the site of attachment (Field et al. 2012). Larger tags, if attached by these methods, would require larger meshes and greater quantities of epoxy. Hence, minimising tag footprint is important, and this further exemplifies the usefulness of using CFD to efficiently and quickly evaluate the pros and cons of different tag design and size choices. It is also important to note that the effect of tag-induced drag is likely to be greater as the ratio of tag to animal volume increases (Kyte et al. 2018), and minimising tag frontal cross-sectional area should also be undertaken where possible (Rosen et al. 2017). Ultimately, to reduce drag, tags should be designed to be more streamlined in line with the contours of the animal being tagged, to achieve smooth flow reattachment downstream of the tag (see tag B; Fig. 4). For this, an increase in size (and thus volume and/or cross-sectional area) could be justified.

We demonstrated that device positioning is crucial in determining tag-induced drag, as evidenced by the non-linear relationship between drag and tag position (Fig. 5). This concurs with the results of Vandenabeele et al. (2014) who observed strong and non-linear effects of tag position on induced drag on a model cormorant in a wind tunnel. Similarly, Tudorache et al. (2014) documented that for swimming eels tagged with biologging devices, placement of a tag in a non-optimum position, compared to an optimum position, could result in a 15% reduction in critical swimming speed and a significant increase in oxygen consumption rate while swimming. Our results also showed that the effect of tag positioning on drag is significantly dependent upon the shape of the tag, and that the variability in the effect of tag positioning for tag B is almost half that for tag A. This demonstrates that improving hydrodynamic design can reduce the impact of positioning *per se* on device-induced drag.

In practice, the choice of tag positioning will also depend on the form of the animal and is further compounded by the fact that the positioning of a tag can affect both the quality and quantity of data collected (Watson & Granger 1998; Jones et al. 2011). For example, GPS data from marine animals can only be obtained when individuals surface for a long enough duration to receive a satellite fix, and for this reason tags are routinely placed on areas of the animal that are exposed most frequently and for the longest periods, for example on the head of pinnipeds (Lake et al. 2006). This is pertinent also for researchers deploying satellite transmitting devices with the aim of maximising the number of successful transmissions, such as uplinks to the Argos network (Service Argos, Toulouse, France). In such cases it may be that the optimum position of the tag for data acquisition or transmission purposes could well be the least suitable position for minimising drag (Watson & Granger 1998; Jones et al. 2011). In such cases, researchers must consider the trade-offs of successful data acquisition with device effects, or consider how they might modify their tags to achieve a more desirable outcome (Jones et al. 2011); for example, researchers could consider using alternative technologies, such as Fastloc-GPS devices, that require only very short durations at the surface (< 1 s) to acquire satellite fixes (Dujon et al. 2014), so that tags can be placed at optimum (i.e. drag-minimising) positions on the animal that are exposed for shorter durations. The method of attachment will also determine how accurately the tag can be positioned and orientated on the animal. For example, tags that are attached by hand (such as tags glued to seals) can be positioned more accurately than a tag attached using a pole e.g. to a cetacean, (Stimpert et al. 2013). The position of tags may also shift during their attachment period (e.g. suction cup tags). CFD offers the opportunity to explore the effect of drag of tags positioned anywhere and in any orientation on the subject animal (Fiore et al. 2017).

Tag position also affects the signals that are recorded - consider for example an accelerometer: the signal received from a device placed on the head will be very different to that of the same device placed on the back of an animal, given that accelerometers are sensitive to tag orientation (Shepard et al. 2008). This factor would likely also play a part in determining the final choice of device positioning. Managing these trade-offs is challenging and requires that ecologists understand the behaviour of their study species and the functioning of their tag, so that they can make appropriate decisions about where to position a device and understand the drag-impacts of their choices (Jones et al. 2011); this can be fully explored for different species and different devices using CFD.

Projects involving tag deployments are diverse and it is not always possible for researchers to rely solely on “off-the-shelf” tags purchased from commercial companies, with many researchers instead resorting to building their own (Kwok 2017). However, there is currently limited advice for researchers who are developing their own tags about how to quantify the drag of their tags and hence how to minimise impact. Here, we fill this gap by providing a step-by-step guide that ecologists can follow to assess tag-induced drag in a quick and efficient manner using CFD techniques (appendix S3), which will aid more researchers to report on the drag-impact of their tags. The guide is written for use with the standard CFD software ANSYS Fluent, used also by other ecologists (Pavlov et al. 2007; Hazekamp et al. 2010), and guides users through the process of modelling the drag impact of tags, from importing the tag design and animal geometry files into the software, through setting up the computational environment and on to running the CFD simulations. The guide will also help in establishing interdisciplinary collaborations with engineers, and aid researchers across the biologging community to increase their understanding of tag-induced drag and work towards best practices in tag design, without the need to rely on collecting logistically challenging empirical data, for example through the use of wind tunnel experiments (Vandenabeele et al. 2014).

In this study, we have focused on measuring drag with respect to frontal flow, i.e. a rigid (or stationary) seal in a field of non-turbulent water (steady-state assumption), including at different flow velocities. This modelling approach can be extended to consider lateral flow, as seals also perform turns or may swim at an angle relative to water current (and in doing so can experience lateral hydrodynamic drag forces). Note that this is different to changing the orientation of the tag on the animal, as demonstrated by Shorter et al. (2014). The drag forces incurred by tags are likely to change markedly in each of these circumstances and hence are also important to bear in mind. Such investigations can be undertaken with a simple extension of our step-by-step guide, by rotating the model animal in the computational environment so that it is lateral to the oncoming flow (see appendix S6 for a first investigation of this).

The CFD method presented here offers a quick and efficient way to determine the best tag (for reducing drag) for the animal being studied, by considering multiple factors including tag design, size and position. However, researchers planning on using CFD must be aware of its limitations. CFD relies on approximate, numerical solutions to the governing fluid dynamic equations, and so there will always be some discrepancies in absolute force predictions between independent studies; we have highlighted some key comparisons between our results and those of similar works (Hazekamp et al. 2010; Kyte et al. 2018). We provide necessary further detail on the limitations of CFD in appendix S2, which we encourage the reader to consult for guidance.

This work has demonstrated the value of an interdisciplinary approach, harnessing engineering techniques to design minimal impact tags and efficiently assess their relative drag loading. While CFD has previously been utilised to measure the impact of tags (appendix S1), its use has largely been limited to researchers with substantial prior CFD modelling expertise (Kyte et al. 2018). The methods we use here are standard for aeronautical design (Jameson & Vassberg 2001) and our guide offers new opportunities for further collaboration between engineers and ecologists - particularly for researchers novice to CFD techniques.

Finally, most existing guidelines for tag impact do not advise on appropriate tag size, placement positions or configurations (Rosen et al. 2017) and many are relatively naïve to the impacts of drag that are most relevant to marine and aerial applications (see appendix S7 for an overview). We anticipate that the reporting of drag values in future publications may help improve future guidelines and address recent requests in the literature for improved reporting of impacts (Bodey et al. 2017; Lameris & Kleyheeg 2017) and better assessment of tag-induced effects (such as drag) prior to deployment in the field (Lear et al., 2018). Whilst we do not expect our findings to be taken up as formal guidelines, nor the use of CFD to be made compulsory, we hope that this work, and specifically our step-by-step guide (appendix S3), will aid the biologging community in achieving this.

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Author Contributions

WPK, DSN, BJE, RPW, LB, TBS, JCB conceived and designed the research; DSN, BJE, HB, SW and WPK undertook the analyses, with feedback from WPK, LB and RPW. WPK led the writing of the manuscript. DSN, BJE, HB and SW wrote the step-by-step guide to running the CFD simulations. PH created the tag B geometry. LB, RPW, DSN, BJE, JCB and TBS contributed critically to manuscript drafts. All authors gave final approval for publication.

Data Accessibility

Data are available from figshare: https://doi.org/10.6084/m9.figshare.8152943. These data are under embargo until 1 August 2019.

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Tables

Table 1. The dimensions, volume, drag coefficient (C_d) (mean ± standard deviation) and percentage increase in C_d over the baseline case (seal with no tag) (mean ± standard deviation) of tag designs A and B. Means and percentage increase of drag are calculated over the range of positions tested (1-9).

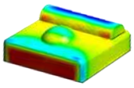
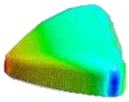
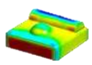
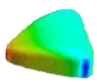
Tag	Form	Dimensions (L x W x H; cm)	Volume (cm^3)	Drag coefficient (C_d) (mean ± SD)	Drag coefficient % increase over the baseline (no tag) case (mean ± SD)
A		10 x 7 x 4	280	0.075 ± 0.002	27.4 ± 4.2
B		11 x 10 x 4	440	0.064 ± 0.001	8.9 ± 1.8

Table 2. The drag force (N), power requirement (W), drag coefficient (C_d), and percentage increase of C
baseline case (seal with no tag), across all positions. Note that negative C_l values equates to downforc
Results shown are for the simulations at 5 ms^{-1} but apply equally across all swim speeds tested (see Met

	Tag	Position	Position (mm)	Drag (N)	Power (W)	Drag coefficient (C_d)	C_d increase over baseline case (seal with no tag) (%)	L coef (
	None	NA	NA	101.3	506.6	0.0588	NA	0.0
	A	1	215.75	125.1	625.5	0.0726	23.5	0.0
	A	2	325.37	122.5	612.3	0.0711	20.9	0.0
	A	3	411.47	127.0	635.0	0.0737	25.3	0.0
	A	4	580.60	132.5	662.6	0.0769	30.8	0.0
	A	5	667.69	133.8	669.1	0.0777	32.1	0.0
	A	6	783.83	133.9	669.5	0.0777	32.1	0.0
	A	7	900.90	131.7	658.3	0.0764	29.9	0.0
	A	8	968.21	130.6	653.1	0.0758	28.9	-0.0
	A	9	1083.44	125.1	625.5	0.0726	23.5	-0.0
	B	1	215.75	108.4	542.1	0.0629	7.0	-0.0
	B	2	325.37	109.8	548.8	0.0637	8.3	0.00
	B	3	411.47	112.0	560.0	0.0650	10.5	0.00
	B	4	580.60	113.4	566.9	0.0658	11.9	0.00
	B	5	667.69	112.0	560.0	0.065	10.5	-0.0
	B	6	783.83	111.3	556.6	0.0646	9.9	-0.0
	B	7	900.90	109.8	548.8	0.0637	8.3	0.00
	B	8	968.21	108.9	544.5	0.0632	7.5	0.00
	B	9	1083.44	107.9	539.4	0.0626	6.5	0.00