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Equine Exercise Physiology: A Literature Review on the Cardiology of the Racehorse & Performance-based Abnormalities

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Abstract

The success of the Irish Thoroughbred in racing is largely attributed to its remarkable cardiovascular system, amongst other advantages. Compared to other racehorse breeds, they have superior basic cardiac and haemodynamic parameters including heart weight, stroke volume and blood volume at rest, and during exercise, they are greatly able to increase their cardiac output whilst having the ability to call upon a huge splenic reserve and divert blood for increased pulmonary flow. The correct training plans and methods are crucial for horses to develop their cardiovascular system sufficiently and Ireland has a great reputation and history for breeding superior racehorses, developing some of the best facilities, trainers and personnel in the world. There are however a number of performance-based cardiovascular abnormalities seen in the Irish racehorse, not limited to arrhythmias, atrial fibrillations, exercise induced pulmonary haemorrhage and sudden death syndrome. While racehorses are better equipped than most to deal with these problems, care must be taken in training and racing to ensure the correct recovery is taken whilst not pushing individuals past their physiological limit. To correctly manage these abnormalities, a number of new methods and programmes are currently being applied in Ireland, whilst the recently formed Irish Thoroughbred Welfare Council is in place to correctly supervise thoroughbred health and prosperity going forward.

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List of Abbreviations

kg = Kilogram

ECG = Electrocardiogram

bpm = Beats Per Minute

ml/min = Millilitres per Minute

MAP = Mean Arterial Pressure

DP = Diastolic Pressure

SP = Systolic Pressure

mmHg = Millimetres of Mercury

TPR = Total Peripheral Resistance

CO = Cardiac Output

SA node = Sinoatrial node

nmol = Nanomoles

O_2 = Oxygen

SV = Stroke Volume

L/min = Litres per minute

RBC = Red Blood Cell

EIPH = Exercise Induced Pulmonary Haemorrhage

CPFI – Cardiopulmonary Flow Index

VO_2 = Oxygen Consumption

$VO_{2\,MAX}$ = Maximal Oxygen Consumption

LV = Left Ventricle

AV node = Atrioventricular node

APCs = Atrial Premature Contractions

VPCs = Ventricular Premature Contractions

AF = Atrial Fibrillations

PCV = Packed Cell Volume

IF = Interstitial Fibrosis

RTE = Radió Teilifís Éireann

1 Introduction

1.1 History

Horses have been synonymous with culture and folklore in Ireland throughout history, and they include many notable breeds that are recognised worldwide. These include the Connemara Pony, a small durable breed from the western provinces well-known for show jumping and breeding, the Irish Cob, historically used by the Irish Travellers for pulling wagons and caravans, and the Irish Draught, a workhorse breed that was traditionally used for ploughing fields, pulling canal boats, used in cross country events such as fox hunting. The Irish Draught was also notably the breed first used in a form of racing known as the steeplechase, which is a roughly 4 miles long cross-country race that was first raced in County Cork in Ireland between the steeples of two churches in different towns [1].

Amongst these national breeds, the Irish Sport horse (otherwise known as the Irish Hunter) and the Irish Thoroughbred stand as two of the most recognised and distinguished sport horses in the world. For the past two hundred years, the Irish racehorse has stood at the forefront of horse racing, notably in flat racing, jump racing, eventing and dressage. In particular, the Irish Thoroughbred has shown exceptional success in both flat and jump racing, routinely beating other Thoroughbreds in the events on the Irish, English and French sporting calendars.

It is common throughout all sports for different factions to have different opinions of who belongs to the greatest athletes within a discipline, and this is no different in the world of horse racing, however five names which feature on almost every list of the greatest racehorses are the Irish-bred Thoroughbreds Yeats, Sea the Stars, Dawn Run, Zarkava, and perhaps the greatest name of all, Arkle [2-4].

Yeats won fourteen races out of twenty-two during her career, including a four-in-a-row win in the Gold Cup at Ascot, while Zarkava went seven years unbeaten in flat racing on the French circuit. Sea the Stars finished second in his career only once across Ireland, the UK and France, winning everything else in his path leading to being described as “having no flaws, mentally or physically” [5] and Dawn Run can claim to be the only horse to win both the Gold Cup and Champion Hurdle at Cheltenham Racecourse. Arkle is known for winning an outstanding twenty-seven races out of thirty-five, whilst placing in the remaining eight raced. He was so renowned for his success that the handicapping rules had to be changed in order to compensate for his ability [6] and Cheltenham now have an event open for horses

five years old and above named after him, with a statue built in his honour in place at the stadium.

Figure 1: Image of the Irish Thoroughbred "Arkle" [7]

1.2 Genetics & attributes

A lot of these successes can be attributed to the calibre of studs in Ireland including Tattersalls Stud in County Kilkenny and Coolmore Stud in County Tipperary, to the quality and experience of horse trainers such as Aidan O'Brien and Willie Mullins, and the availability of wide-open plains like the Curragh Plains in County Kildare, which has historically always been associated with horses and horse racing, as well as being home to the Curragh Racecourse, a renowned flat racing course. However, the fundamental success of the Thoroughbred over other horse breeds comes down to a superior anatomy and physiology. When the three founder Arabian stallions; Darley Arabian, Godolphin Arabian and Byerley Turk [8], known for their speed and agility, were brought to England and crossed with native workhorse breeds of the United Kingdom in the 1800s, they formed the genetic line of Thoroughbreds, who combined the skills of the Arabian breeds with the endurance and power of workhorses. It is remarkable to think that not only do almost all modern-day Thoroughbreds descend from those male lines, but the General Studbook registry is also able to identify seventy-four mares who made up the female line of parentage [9].

In this genetic line, the most notable performance-based attributes include their strong muscular composition, which is seen to have large amounts of C-variant at the myostatin gene in successful horses and family trees [10]. There is an extraordinary lung capacity with a tidal volume of 5 litres at rest that can expand to 55 litres in exercise [11], compared with 500 millilitres tidal volume and 5 litres capacity in the average human. At the base of it all, Thoroughbreds have a cardiovascular system that can produce a cardiac output of up to 300 litres per minute during exercise in the greatest athletes [12] and can induce a total red blood cell count of 65% from splenic reserves when needed.

In this literature review, I will hope to give a proper insight to the remarkable cardiovascular system of the Irish Thoroughbred racehorse, namely the work performed by the heart and the effect of exercise on the heart, while also outlining a thorough review on performance-based abnormalities, such as atrial fibrillations and sudden death syndrome.

2 Cardiovascular system

2.1 Horse Heart

The equine heart has the same anatomy and function as all mammals; it is a muscular organ divided into four chambers consisting of two atria and two ventricles. The left atrium and ventricle pump oxygen-rich blood into the aorta and other systemic arteries towards the organs and musculature of the body, while the right atrium and ventricle collect oxygen-poor blood and pump it towards the pulmonary system for carbon dioxide and other waste exchange. These chambers are connected by valves that open and close during systole (cardiac muscle contraction) and diastole (cardiac muscle relaxation) to ensure correct direction of flow. The equine heart weighs approximately one percent of total body weight in the average horse [12] and can be up to 1.3-1.4% in the greatest athletes. This gives the average Thoroughbred weighing between 450 to 500 kilograms a significant advantage over Standardbred horses for example, weighing between 410 to 450 kilograms, [13], and other racing breeds as the average Thoroughbred heart size therefore weighs in at 4.5 to 5 kilograms and can be as large as 6-6.5kg in the most elite racehorses. For comparison, the average human weighing 62kg [14], has a heart weighing around 350 grams [15] or 0.5% of total body weight, giving the horse a much larger cardiovascular pumping apparatus in comparison to other mammals.

While there has not yet been substantial research of post-mortem heart weight measurements taken on Irish Thoroughbreds, the famous American Thoroughbred Secretariat (who won the

Triple Crown in 1973 and finished thirty-one lengths clear of second place in that years Belmont Stakes [16] had its heart weight measured at over 10 kilograms during its postmortem examinations without growing larger through pathological processes [17]. Furthermore, researchers of ECG studies on the equine heart have found a direct correlation between larger hearts and greater performance [18], leading to a huge interest in echocardiogram and ultrasound usage to estimate heart weight in the living Thoroughbred horse. While it is established in the world of sports that regular aerobic exercise will lead to heart hypertrophy and greater oxygen carrying capacity, genetics will also play a role in the size of an individual's heart. Frankel, a great British racehorse sired by another great Irish Thoroughbred Galileo, is thought by vets to have an unusually large heart with a body weight measured around 604 kilograms [19] meaning a suspected heart size of between seven and eight kilograms.

In mammals, the left side of the heart has both a notably thicker cardiac muscle wall and larger inner area as it is the side pumping oxygen-rich blood around the body and so has developed to allow for maximal blood pooling per diastole as well as providing extra protection to the left sided chamber. In her review of the heart size in racehorse cardiology, Rikke Buhl [17] also states that endurance training will lead to a further increase in left ventricle side over the right side. While there has been no direct research on the genetics behind equine myocardial hypertrophy, it has been found that Thoroughbreds have an increased left ventricle volume and thickness of the muscle wall compared to the normal horse and that both training and age contribute to increase in size. As the horse will grow in body size as it gets older, so will the size of the heart in order to allow for necessary pumping, accommodating their growing size. In their study on four groups of Thoroughbreds sorted only by length of training programme, Kubo et al [20] found that the group who undertook the longest training programme had both the highest average heart weight (approximately 4.8 kilograms) and the greatest left ventricular wall thickness (4.34 centimetres), with both parameters getting directly smaller for the remaining three groups, as was seen in the fourth group that had no training (approximately 4.1 kg and 3.97 centimetres respectively). They also found that while each group had a smaller right ventricle size compared to the left ventricle, there was no significant difference in thickness of the right ventricle chamber or myocardium between each group, which highlights the importance of the left ventricle in Thoroughbreds for effective cardiac function compared to the right ventricle, as well as

showing the inherent developmental ability of Thoroughbreds to form larger left ventricles (and thus overall heart size) in order to maximize performance.

2.2 Stroke Volume

Electrical conduction of the heart beginning in the sinoatrial node and later the atrioventricular node and through Purkinje fibres allows contraction of the atria, followed by the ventricles in the physiological phase known as systole. Blood is pumped first from the atria to the ventricles and afterwards from the ventricles to the aorta/pulmonary artery, before the muscles relax, and the chambers fill with blood again during the phase of diastole. The volume of blood ejected from the left ventricle during this time is known as stroke volume and is one of two major components determining the work performed by the heart. Influencing stroke volume is the strength of myocardial contraction, the ability for the muscle to relax and pool blood during diastole and size of the ventricle chamber. The average horse has a stroke volume of one litre at rest, which can increase to 1.7 litres during exercise [21]. In comparison, stroke volume in a Thoroughbred weighing 500kg is 1.3 litres and this can increase to between 1.6-1.9 litres during exercise [12]. In a study on trained Thoroughbreds, Weber et al [22] found stroke volume to be 1.34 litres at rest while reach 1.58 litres when walking steadily. Sea the Stars weighs approximately 600kg [19], which would give him an estimated stroke volume of 1.56 litres at rest, though with his huge racing pedigree it is likely that the actual stroke volume is probably higher than the volume estimated.

2.3 Heart Rate

The other major component for determining the work performed by the heart is heart rate, i.e., the number of times the heart goes through one beat (or one systole and one diastole) per minute. While Weber et al [22] measured the average resting heart rate of Thoroughbreds training in their study at 48 bpm, the resting heart rate of the Thoroughbred is generally between 20-30bpm [12], and these values would be consistent to the resting heart rate of other horses [23, 24]. When compared to the resting heart rate of the average human, 50-60 bpm, this follows the theory of metabolic rates as expected, in which resting heart rate is inversely related to body size and so larger animals will have lower resting heart rates. This can also be seen in the horse as it ages, with two-year-old foals normally having a resting heart rate around 45-60 bpm [25]. Ohmura & Jones [26] found resting heart rate of 1 week old foals to average at 106 bpm, with the resting heart rate of older horses averaging at 32 bpm.

2.4 Cardiac Output

The amount of blood pumped from the heart is defined as cardiac output and can be calculated by multiplying stroke volume by heart rate. The cardiac output for the average horse at rest is 25 litres [12], but of course this will vary with each horse depending on the size of their hearts, left ventricles and thus stroke volume at any given heart rate. As stroke volume is higher in Thoroughbreds than the average horse, cardiac output will measure between 26-39 litres for a resting heart rate of 20-30bpm in an untrained horse. In their study on the effect of exercise on cardiac output and oxygen consumption in trained Thoroughbred horses, Weber et al [22] measured resting cardiac output as 106 ml/min per kg of horse, or 53 litres in a 500kg Thoroughbred which has cardiac adaptations for exercise. Butler et al [27] has a similar study measuring cardiovascular and respiratory adaptations of Thoroughbreds to exercise and calculated the average resting cardiac output to be just over 40 litres for their subjects with average weight 440kg.

2.5 Mean Arterial Pressure

Another physiological measurement which should be noted is mean arterial pressure and this will normally remain consistent in varying cardiovascular conditions, with other systems and values compensating for any drop or increase in MAP. In their study on the changes in arterial pressure on a group involving nine Thoroughbred horses throughout several different conditions, Pratt et al [28] measured normal mean arterial pressure to be between 71-110 mmHg, the same values measured in healthy humans and indeed in most mammals [29]. MAP is calculated by measuring both diastolic arterial pressure (DP) and systolic arterial pressure (SP), with the formular equating to DP + 1/3 (SP -DP). Parry et al [30], measured the normal DP and SP to be 49-105 mmHg and 80-140 mmHg respectively within a group of two hundred and ninety-six horses, including ninety-seven Thoroughbreds, with mean arterial pressure thus calculated at approximately 99 mmHg on average.

The vascular force put on systemic blood flow, or total peripheral resistance (TPR), has a large role in the body's maintenance of blood pressure, as it has a relationship with cardiac output that can also be directly used to calculate pressure (CO x TPR = MAP). If the value for either CO or TPR changes, the other value must also change for MAP to stay between 70-110 mmHg. In response to different physiological conditions, the cardiovascular system of the Thoroughbred, and all mammals, has mechanisms in place to compensate for the changes to either cardiac output (by alterations to stroke volume or heart rate) or total peripheral

resistance (with increased vasoconstriction or vasodilation) in order to maintain blood pressure. Once baroreceptors sense a change in mean arterial pressure, they send this information to the central nervous system, which responds by inducing either sympathetic or parasympathetic innervation from the autonomic nervous system.

2.6 Sympathetic Innervation

When mean arterial pressure drops towards 70 mmHg and lower, baroreceptors in the aortic arch and carotid arteries will sense the hypotensive change and relay this information to the central nervous system. The information is then processed and leads to necessary physiological changes. Heart rate is increased through innervation of the SA node, while venous return of blood to the heart is also increased, meaning an increase of stroke volume, and thus contributing to the needed increase of cardiac output. The sympathetic system also increases vasoconstriction of vessels to increase the total peripheral resistance whenever there is a drop in cardiac output.

There are few studies measuring the changes on catecholamine concentration during exercise, as there is little practical usage of these values to horse trainer and owners, however there is evidence available suggesting that horses can induce similar changes in hormone concentration as humans. In their study on the effect of high-intensity exercise on plasma catecholamines, Snow et al [31] found that Thoroughbred horses were able to increase mean concentrations of both adrenaline and noradrenaline much more than expected based on studies performed in humans, reaching values of 153 nmol per litre of adrenaline and 148 nmol per litre of noradrenaline. These values were one hundred- and forty-eight-fold increase and sixty-seven-fold increases from the respective basal values measured and can have similarities to some studies on performed on humans as Berkin et al [32], found a fifty-four-fold increase in adrenaline. In their study on adrenaline and noradrenaline levels in Esperia ponies, [33] found that the same levels of increase were seen in non-racing breeds during exercise as in racing horse breeds, which would indicate that the large rise of sympathetic hormones seen during exercise in Thoroughbreds is due to a mammalian cardiovascular response to exercise as opposed to an inherent ability of racehorses specifically to increase adrenaline and noradrenaline levels when required.

2.7 Cardiac Output during Exercise

During exercise, total peripheral resistance decreases in the athlete due to vasodilation of vessels around skeletal muscle, allowing blood to be diverted from visceral organs to the

limbs and thorax. The subsequent drop in MAP results in increases to both heart rate and stroke volume, compensating for the drop of TPR while also maximising blood flow and O_2 supply to the muscles.

As mentioned earlier, the Thoroughbred horse has a resting heart between 20-30 bpm, which will increase at the onset of exercise to meet the necessary intensity. What makes the horse a supreme athlete though, and particularly the Thoroughbred horse, is its ability to increase heart rate ten-fold during exercise in order to meet the extra demands put on the heart by the body. When reaching maximal exercise, the Thoroughbred can reach between 220 and 240 beats per minute [12] [25] [34]. Evans & Rose [35] studied the variability of cardiovascular and respiratory parameters between rest and at exercise in six thoroughbred horses (who did not have training-induced alterations) and found the average heart rate during peak exercise to be 222 bpm, with a range of 14 bpm difference found across testing. In their study on the physiological responses of one hundred and two Thoroughbred horses in Ireland to changes in velocity during training, Fonsesca et al [36] the horses were able to reach 220 bpm steadily with the maximum heart rates measured reaching 290 bpm, almost fifteen times higher than the lowest measured heart rates. The average human heart rate doubles/trebles during steady state exercise to reach 130-150 bpm on average, with the maximum heart rate generally estimated at 220 minus their age bpm (e.g., 185 bpm for a 35-year-old average human), showing the remarkable variability that the Thoroughbred horse has in heart rate.

Stroke volume in the horse can increase up to 150% of resting SV, with a 500kg horse increasing from 1.3 litres to approximately 1.6-1.9 litres, and trained Thoroughbreds having a larger increase of up to over 2 litres. Combined with the ability to greatly increase heart rate, cardiac output can increase 12-fold from 6.6 L/min to over 300 L/min in athletes during high intensity exercise [12] [25], which can accommodate a huge decrease in total peripheral resistance while maintaining MAP within the physiological range. In comparison, the resting cardiac output of an elite human athlete can rise from 6 L/min to 35 L/min [37]. Durando et al [38] used lithium dilution to measure cardiac output of thirteen Thoroughbreds before and during exercise and compared these to the expected calculated values. They found that cardiac output measured at approximately 191 L/min at walking pace and rose dramatically to over 327.5 litres per minute at the first gallop and higher again to 382.5 L/min on the second gallop, compared to the calculated 300 L/min and 310 L/min. Evans & Rose [35] measured maximal cardiac output in detrained horses with average weight of 483kg to be 258 L/min, while Butler et al [27], saw cardiac output in seven Thoroughbreds rise 3-fold when walking

and 6-fold during submaximal exercise. While also seeing a significant rise in stroke volume during training of Thoroughbreds, Weber et al [22] found a 6-fold increase in cardiac output from resting to reaching a steady canter.

The literature shows that the Thoroughbreds as a breed can increase their cardiac output largely when moving from rest to a steady pace by increasing stroke volume and heart rate, and for every increase in heart rate thereafter can continue to produce a large functional stroke volume as the intensity of work increases. Holding such a large cardiac output for an extended period is another issue however, and one which leads to both pathophysiological and pathological processes in many cases, as will be discussed later.

2.8 Blood Volume

The horse has a circulating blood volume representing 10% of total body weight, which is approximately fifty litres in the average Thoroughbred and can be as large as sixty litres [12] [34]. When comparing the total blood volume between racing breeds and workhorses, Julian et al [39] found that Thoroughbreds, amongst other racing breeds, have a total blood volume 1.5 times larger than Percheron draft horses, although of course they are comparatively much lighter than the working breed and much of the extra blood volume is down to a notably much lower body fat percentage rather than increased vascularisation. When researching blood volumes in different horse breeds, Marcilese et al [40] found that thirty-one Thoroughbreds had a total blood volume of 10.31% body weight compared to 7.71% in saddle horses and 6.14% in draft horses.

The normal haematocrit for a horse is 35% but Thoroughbreds can reach an RBC count as high as a 65% of total blood volume, with the maximal haematocrit level in humans known to be 50% and paling in comparison. In their same study, Marcilese et al [40] found that the Thoroughbred subjects had a normal haematocrit of 42.7% at rest, with the mean corpuscular volume of almost four litres for every one hundred litres of body weight (twenty litres in a 500 kg horse or twenty four in a large Thoroughbred like Frankel or Sea the Stars), compared to 37.7% saddle horses, and this can be up to two-fold larger than haematocrit seen in work horses [39].

2.9 Spleen and Red Blood Cell Count

The largest reason for this extraordinary ability to raise RBC count is that the horse has a spleen larger than that in other mammals compared to body size [12], and the Thoroughbred

can call upon a larger splenic reserve than other breeds, with almost 50% total red cell count stored in the spleen at rest. Kline & Foreman [41] studied the size and weight of spleens in the Thoroughbreds compared to stock horses, draft horses and Arabian type horses and expressed the results as percentage of body weight. They found that the spleen in Thoroughbreds was twice as large proportionally to the draft breeds, two thirds larger than stock horses and almost 50% larger than the Arabians. Malikides et al [42] showed how the horse can call upon splenic reserves to such an extent that following donating of eight litres of blood five times over a period of eight weeks, no significant drop in blood values is shown. Arkle [2-4] was widely known to have been the greatest athlete of his kind at the time and folklore suggests his success was due to drinking two pints of Guinness every day, with the high iron content of the drink contributing to a larger red blood cell volume than his competitors. However, it would be more scientifically accurate to suggest any outstanding haematocrit or blood volume derived from a large anatomical and functional splenic reserve.

The functional haematocrit in horses is greatly reduced following splenectomy [43] and it can be concluded that the proportionally functional size of the Thoroughbred spleen is hugely responsible for maintaining blood volume and so cardiovascular function. This was also reported by Kline & Foreman [41], finding that a greatly reduced stroke volume during moderate exercise contributed to low cardiac output and poor performance in splenectomised horses compared to the control subjects.

The anatomy of the horse's spleen hints at how they can maintain a huge splenic reserve [44], as there is a non-vascular area for storing red blood cells equal to the size of the area taken by vessels. All arterial branching was found to be intraparenchymal, maximising the potential of the parenchymal units. In their study of the horse's splenic volume using ultrasound, de Solis et al [45] found that the volume of the spleen was twice as large in the living horse compared to post mortem examination, but that the blood volume in the spleen was six times lower than normal following administration of adrenaline, showing that upon large catecholamine induction, such as in exercise, the spleen almost totally empties its red blood cell supply for the horses functional use.

In their study on the effect of a splenectomy to the haematology of the horse, Persson et al [43], found that the haematocrit proportion of splenectomised horses in the venous return was almost identical to the venous return haematocrit of normal horses following induction of adrenaline, however that the total haematocrit in venous return and systemic blood was

greatly reduced following removal of the spleen, which highlights the role of the horse's spleen in storing large quantities of RBCs at rest but also greatly adding to venous return, stroke volume and thus cardiac output on onset of exercise compared to other species. When you then consider the proportionally larger spleens in Thoroughbred horses than spleens seen in other breeds, it becomes clear why their haematology and cardiovascular system is superior.

2.10 Pulmonary flow

Cardiac output can be described as the volume of blood pumped from the left ventricle per minute entering systemic blood flow, whereas the blood ejected from the right ventricle per minute towards pulmonary flow does not fall into this category. Instead, the total blood flow between the right atrium and immediately after the left ventricle at the aortic root is measured as cardiopulmonary blood flow, consisting of blood in the heart, lungs and all pulmonary blood vessels. While cardiopulmonary flow is normally not of much interest in the field of human sports and exercise parameters, these values can be important for the diagnosis and evaluation of exercise-induced abnormalities in the Thoroughbred such as Exercise Induced Pulmonary Haemorrhage (EIPH). Cardiopulmonary blood flow has shown to have no direct correlation with cardiac output, however Levinson et al [46] found that it correlates strongly with stroke volume in mammals.

Van Aarde et al [47] measured the cardiopulmonary flow index, i.e., the ratio of cardiopulmonary flow to stroke volume, in different horse breeds at rest and found that showjumping breeds had a relatively larger index than Thoroughbreds, however as the Thoroughbred has the largest stroke volume per unit of body weight of any horse breed this could be expected. Following on from that research, Guthrie et al [48], attempted to measure cardiac function in the Thoroughbred by using cardiopulmonary flow index. In their study of two groups, one control group and another suspected of having toxin-induced myocarditis, they found that there was no significant difference between cardiac output between either group. However, by measuring cardiopulmonary flow index they found that there was a significant difference between each group, indicating how CPFI may be a more accurate unit of measurement to take in clinical trials and medical testing of cardiopulmonary disease.

3 Exercise & training

3.1 Racing

There are several different types of races which Thoroughbreds compete in internationally and each country & region have their own preferences. In Australia and the USA in particular, harness racing is popular in which each horse carries a carriage with the jockey/driver, and this can also often be viewed in Kincsem Park in Budapest. Endurance racing involves competing over enormous distances taking a full day or days and are mostly associated with the Middle East or areas with long open plains, again in Australia and USA. In Ireland, as well as France and the United Kingdom, Thoroughbred horses mostly compete in Flat racing, in which horses race over a short, flat distance and sprint speed is the priority, and Jump racing, also known as National Hunt in which competitors race over hurdles and obstacles in a cross-country race that demands more agility, stamina and power than Flat racing does.

Horses are selected early on in life and trained for either discipline depending on characteristics shown at a young age and there is huge physical & financial effort made to make each horse as competitive as possible. Gramkow & Evans [49] tested the heart rates of twenty-five Thoroughbreds over a range of exercise intensities and tracked their maximal velocities over each exercise, finding a direct correlation between the maximal heart rate of each horse with the money earned by each horse per race. Kamiya et al [50] studied the resting heart rate and heart size of the top Thoroughbred horse in Japanese racing history and concluded that his superior physiological traits directly contributed to his racing and economic success. It can be said that it is optimal for trainers and owners to spend as much as necessary on buying the foals and yearlings with the best genetic traits for either Flat racing or National Hunt racing and to equip each athlete with the best training plans and methods for maximising physiological adaptations, as well as ensuring sufficient rest and nutrition daily.

3.2 Training

Training programs in the horse have the same principle as the modern human athlete. They generally begin with low intensity, long distance aerobic training in which the horse undergoes cardiac and respiratory conditioning in order to undergo the appropriate adaptations to exercise, while also improving the strength and power of their skeletal muscle. Later in a training season, work will switch to include high intensity anaerobic training, preparing the athlete for maximising their speed and to maintain this velocity for longer periods. If improper care is taken towards rest and nutrition or if the workload exceeds the ability of the horse, overtraining will occur with a loss of performance and general ability

seen. Following any injury or illness, the period of rest and recovery is known as detraining and there are losses of anatomical and physiological adaptations that the horse may have seen.

It is in the benefit of both owners and trainers to minimize any time spent detraining in order to maximize athlete performance and thus earn as much as possible for each race & race season, however there is great ethical concern over rushing horses back too soon and risking further injury, illness or death. This makes any training program used important to balance the health and welfare of the horse with performance and economic gain, one which trainers and owners of Thoroughbred horses have been able to maintain successfully, particularly Irish trainers and owners. When you see that Irish studs like in Ballydoyle Stables in County Tipperary would go as far as to build a like-for-like replica of Epsom Downs Racecourse [19] to prepare their horses for the Epsom Derby in June each year, it is no wonder that Irish Thoroughbreds are performing so well with Irish trainers and training plans every year.

3.3 Training adaptations

There has been abundant research on the physiological adaptations of Thoroughbreds following regular training and while most studies focus on the changes to VO_2 and $VO_{2\ MAX}$, there have been several studies covering the alterations to cardiac function. Kubo et al [20] studied the changes to heart weight and left ventricle size to sixty-one Thoroughbred horses following 4 training programs. Group A undertook regular training, Group B had the same length of regular training following a period of detraining, Group C had begun a couple of months of training and Group D acted as a control with no training experience. They found that there was hypertrophy of both the right and left ventricles following the initial few months of training, with left ventricle size being proportionally twice as large as the right side in each group. They also found that mean heart weight and ventricle sizes in Groups B and C to be relatively equal in size, concluding that ventricle size (and thus stroke volume) needs to be maintained in horses through regular training. Buhl [17] concluded in her study on Thoroughbred horses and heart size that increased heart size correlated directly with race performance and that trained athletes always had a significantly larger heart size than untrained ones. She also noted that the heart size of National Hunt athletes was proportionally bigger than Flat racers, from which it can be stated that horses that train over longer distances will have greater cardiac hypertrophy and a larger heart size is key for better performance over longer distances, whilst also noting that any veterinarians, trainers and owners must take care to understand and be aware of each athletes limitations to avoid risking ventricular

abnormalities or sudden death. Through using echocardiography, Young [51] found that Thoroughbreds in flat race-type training showed similar increases to end-diastolic filling as in National Hunt training, however a subsequent increase to LV wall diameter caused by power and sprint training resulted in decreased fraction of stroke volume ejection and so a proportionally lower cardiac output than would be seen (and needed) for success in Flat Racing.

Evans et al [52] measured both heart rate and plasma lactate levels of Thoroughbreds after training and found a direct correlation between both parameters and quality race performance, while Harkins et al [53] found that increased ability to raise heart rate during exercise correlated occurred in faster horses with improved running ability and that training at submaximal levels was the best way to attain the desired results.

Ohmura et al [54] measured the physiological changes in both trained and untrained Thoroughbreds over the first year of training and found that along with the expected changes to body mass and $VO_{2\,MAX}$, the trained Thoroughbreds had significant increases in both stroke volume and cardiac output than the untrained group, with initially huge increases to both parameters before steady rises in both with prolonged training. Another interesting find in their study was that haematocrit for trained horses was lower than untrained at rest without a decrease in red blood cell count, which would suggest that the trained horses were able to call upon a greater red blood cell supply from the spleen during exercise and so greatly improve their O_2 carrying capacity. All increases to $VO_{2\,MAX}$ were mostly attributed to cardiac hypertrophy following training and thus improved overall blood supply. Evans & Rose [35] also found the improvements to $VO_{2\,MAX}$ during steady submaximal training of Thoroughbreds to be directly attributed to the capacity of the heart to pump blood, with larger hearts developed in training to lead to improved performances.

Butler et al [27] studied the cardiovascular changes to a group of Thoroughbreds during exercise and found that cardiac output was able to increase six-fold, while also finding large increases to both packed cell volume and haemoglobin from the increased red blood cell supply in exercise, allowing for a decrease in the partial pressure of oxygen. However, they also noted that the large increase in cardiac output was not compensated by an equal reduction in TPR and so hypertension was seen in both systemic blood vessels and pulmonary blood vessels, particularly at the highest work intensities. Along with the high mean arterial pressure seen, blood temperature was reported to rise as high as four degrees higher than baseline due

to two-fold increases in blood lactate and subsequent reduction in arterial pH, which were not fully compensated through increased respiratory alkalosis. This indicates that prolonged periods of high intensity work can have serious adverse effects on MAP and thermoregulation, which if prolonged will lead to the multitude of performance-based abnormalities seen in modern racing and particularly in Thoroughbred horses.

Another point that should be highlighted in strenuous training and racing in Thoroughbreds is the large haematocrit which elite athletes are able to produce. While this is beneficial for optimal red blood cell supply, and this O_2 carrying capacity, the increase in cell count will lead to increased viscosity and risk the formation of thrombi and embolisms. Fedde & Erikson [55] found that due to the increased packed cell volume, the viscosity of blood appeared to double during intense exercise and while this could not cause pulmonary hypertension alone, it may be majorly linked to exercise-induced pulmonary haemorrhage development.

The research shows that optimal race performance is resulting from a correct training programme and that cardiovascular parameters increase with time during aerobic training. However, they also find that if pushed beyond their physiological limits, horses will begin to develop pathophysiological and pathological processes. While injury and death in young Thoroughbreds is mostly due first to musculoskeletal defects or congenital defects [56] secondly from gastrointestinal tract problems and respiratory disease [57] and while most reasons for Thoroughbreds retiring are a result of musculoskeletal injuries developing during racing, several horses who reach racing age will develop performance-based abnormalities such as arrhythmias, atrial fibrillations, exercise pulmonary induced haemorrhage and sudden death syndrome.

4 Performance-based abnormalities

4.1 Arrhythmias

Arrhythmias may be seen in the horse without signifying pathophysiological processes, in which normal sinus rhythm is interrupted. A second-degree atrioventricular block, in which the AV node does not carry the electrical conductivity from the SA node during every systole, can occur as a result of increased parasympathetic innervation [58] [59]. The depolarisation does not fully carry into the ventricles, but the result is simply a singular incomplete contraction (asystole) amongst normal contractions and would expect to disappear with increased sympathetic innervation during exercise. Another physiological arrhythmia that may also be seen with increased parasympathetic innervation would be sinus block, in which the

SA node does not initiate depolarisation as every time and so would again result in singular asystole amongst regular contractions before disappearing with increased sympathetic innervation. Finally, sinus arrhythmia can be seen physiologically [58] [59] simply through auscultation during respiration, with the process of inhalation inducing sympathetic innervation and may cause an increased heart rate, however this would not be enough to be seen clinically alone.

Atrial premature contractions, also known as supraventricular premature complexes, are a form of abnormal arrhythmia, in which myocardial contractions are induced from a point other than the SA node [58] and will add to the base sinus rhythm. In the presence of APCs, heart rate will increase as the SA node continues to fire and so the base rhythm will increase. The ECG will appear normal, however there will be an increase to the number of each wave seen and the interval between wave may be shortened significantly. Four or more atrial premature contractions in a row is termed as atrial tachycardia, and if this abnormally fast heart rate is sustained, it may develop to cause more severe problems in the form of atrial fibrillations [59].

Ventricular premature contractions/complexes may also be seen in Thoroughbreds but are both less common and less severe than APCs [58]. An electrical impulse stemming from the ventricles will cause depolarization independent from the atria, so ventricular depolarization and repolarization will appear more frequently on an ECG for each VPC. This will read as an increased number of QRS complexes & T waves between each P wave, which may also appear smaller than usual. Any occurrence of ventricular tachycardia would be considered as abnormal, however there is no real incidence of this developing into more serious pathological problems in the literature.

4.2 Atrial Fibrillations

Atrial fibrillations can be described as an atrial tachycardia in which there is a period of irregular, asynchronous contractions and result in incomplete systoles & incomplete ventricular filling, which will cause ischaemia and other pathophysiological events if prolonged or repeated. Atrial fibrillations are widely considered as the most important arrhythmia in Thoroughbred horses as they are linked directly with performance [60-62] and can develop over a short period of time following prolonged, intense exercise where the demand for oxygen is much greater than the supply delivered [63]. On an ECG reading of atrial fibrillations, P waves will appear frequently but in irregular fashion, with no uniformity

of shape or size, while QRS complexes will maintain normal shape but appear in random order due to the differing depolarizations of the atria and ventricles [58]. If heart rate returns to normal rhythm and frequency after an atrial fibrillation, it is known as paroxysmal, but any occurrence of fibrillations should be treated immediately in order to resolve quickly and prevent further cardiovascular damage. Occurrence of atrial fibrillations happens in approximately 2.5% of horses [61], however participation in racing will increase the likeliness of fibrillations developing and some studies on Thoroughbred populations show that one horse in every twenty can show signs of AF developing. Other breeds of horses and ponies are seen to never show AFs [64].

4.2.1 Occurrence: Nath et al [65], performed a study on the occurrence and consequences of atrial fibrillation development in over four thousand and five hundred Thoroughbred horses in order to determine the severity of AFs on performance. It was found that approximately 5% of this population exhibited atrial fibrillations at least once after racing, however only one horse in every five are examined after any race, so the actual occurrence of Afs may have been much higher than expected. QRS complex frequency and shape were found to vary among high heart rates, however ECG was needed to confirm whether the arrhythmias were atrial fibrillations or other physiological changes in sinus rhythm. Horses that showed persistent atrial fibrillations had a much higher chance of re-occurrence after being treated, but also that re-occurrence of atrial fibrillations did not correlate with poor career performance and early retirement. Vernemmen et al [66] also found that atrial fibrillations reoccur in horses after treatment if the initial atrial fibrillations were persistent pre-treatment and, in their study, found that the presence of atrial premature contractions five days after treatment correlated directly with atrial fibrillations reoccurrence, so diagnosing APCs may be a useful indicator for predicting AF occurrence in horses.

4.2.2 Recent Irish History: Atrial fibrillations occur more frequently in Thoroughbred horses than in human athletes, however due to millennia of horses being bred for endurance work and Thoroughbreds themselves being genetically bred over centuries for racing, they are also genetically and physically able to cope with AF occurrence. When discussing the heart issues of the Irish Thoroughbred Denman in 2008, Celia Marr [67] explained how following successful pharmacological treatment, no operation would be needed following his previous withdrawal from a race, whereas a human athlete would probably have to have surgery in order to reach the same performance levels again. She stated how almost all racehorses will have at least one experience of atrial fibrillations during racing at some point in their career,

but it does not need to be treated as seriously as it would with humans. Lesley Young stated in the same article there is little way of controlling arrhythmias in horses as we've created a cardiovascular machine throughout history with increased heart size and thus potential for arrhythmia development, but due to being bred for racing, horses can also deal with AFs better. Denman retired three successful years later without further cardiovascular issue, finishing second in the Gold Cup in each of those three years [68]. Sprinter Sacre, another Irish Thoroughbred, also was treated by Celia Marr and was discovered to have post racing atrial fibrillations in 2012, due to an exceptionally large heart size [69]. However, the horse also managed to have another successful 3 years following treatment without further issue before retirement.

4.2.3 Remodelling: Training of Thoroughbred horses is already established to lead to increased heart size, but early studies had shown the growth of cardiac muscle is not uniform with other anatomical structures in the heart and so hypothesised that the occurrence of atrial regurgitation due to incomplete valvular closing can occur more frequently [51]. Studies on both humans [70] and rodents [71] have found that overly intensive long-term training will lead to cardiac remodelling and increase the likeliness of arrhythmogenic behaviour as part of compensation for incomplete ventricular ejection. However, more recent studies on other similar racing breeds such as Standardbreds [72] have suggested that atrial fibrillation sustainability in racehorses is due to electrical remodelling rather than cardiac enlargement or other sources. While the trained horses had structural remodelling, it did not lead to either inflammation or fibrosis which are seen to lead to arrhythmias in other models, while the refractory period instead was shortened and so remodelling of the electrical pathways was found to be the source of fibrillations.

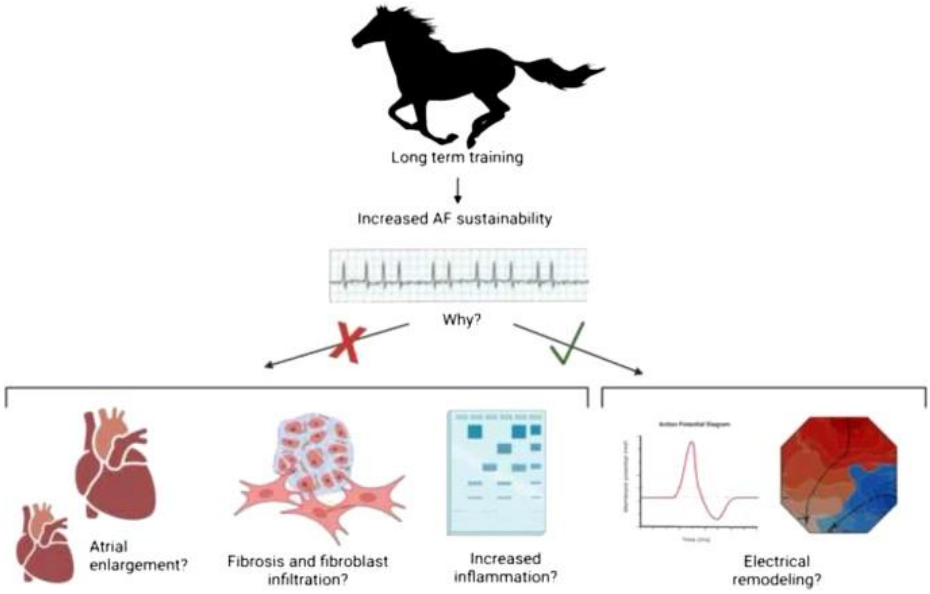

Figure 2: Increased atrial fibrillation sustainability. [72]

4.2.4 Quinidine Treatment: Due to the major cause of electrical remodelling, the most effective drugs for treatment of atrial fibrillations are anti-arrhythmic drugs and the most used of these is quinidine [73] [74] [61]. Quinidine is a Class 1A anti-arrhythmic drug which works to delay sodium channel opening, whilst also having the effect of delaying the refractory period. This helps to increase the depolarisation threshold of cardiac muscle action potentials and so lower conduction, thus slowing heart rate. The opening of calcium channels already creates the plateau phase seen in cardiomyocyte action potential cycle, but additionally delaying of sodium channel opening will help control being maintained over conduction and so return the atrial/ventricular systole return to normal timing.

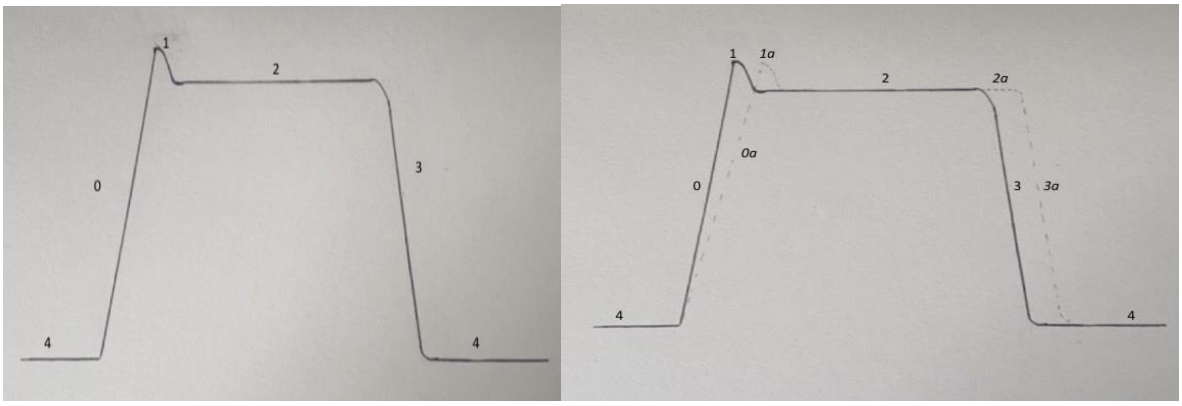

Figure 3 & 4: Image of how a cardiomyocyte action potential looks vs an image of the effect of quinidine (0a-3a) on cardiomyocyte action potentials

Quinidine has always been the first drug used to combat atrial fibrillations in the form of quinidine sulphate [63] [75] [61] [76]. Administration of quinidine sulphate to horses within fourteen days of atrial fibrillation diagnosis will have a significant effect on vagal tone, reducing average heart rate to within the normal resting range and having a great effect on the maintenance of mean arterial pressure at normal, thus reducing the need for compensation through increased heart rate in the first place. While it is an oral solution, it is applied through a nasogastric tube to avoid oral ulceration. According to Bradford et al [73], quinidine sulphate is an effective drug to use in the correct dosage as it has a short half-life and will normally be fully excreted within twelve hours of administration after successfully returning heart rate to sinus rhythm. Quinidine gluconate may also be used, applied intravenously to horses within two weeks of AF occurrence.

Quinidine is being used less commonly in modern medicine however as it is showing side effects more frequently in horses. Amongst the more serious of these include hypotension, ataxia, colic & dyspnoea and can also induce supraventricular tachycardia following treatment, so should not be administered to horses with any history of chronic heart failure or other cardiovascular conditions. According to De Clercq [61], the number of horses which experience side effects in incorrect dosages is as high as 76%, while De Cloedt et al [74] states that quinidine toxicity can lead to sudden death and limits the later effect of cardioversion therapy [76]. In more recent years, administration of quinidine is given concurrently with digoxin, which works on a cellular level to lower calcium release and thus extend the plateau phase of cardiomyocyte action potentials, slowing heart rate further. Muir & McGuirk [77] in their study on pharmaceuticals on horses with cardiac disease that 85% of horses which did not respond to quinidine sulphate alone had successful treatment when digoxin was also administered.

4.2.5 Flecainide Treatment: Flecainide is another drug used to treat horses for atrial fibrillations and is being used more commonly in recent times over quinidine. It is another antiarrhythmic drug, categorised in Class 1C, and works more potently to block sodium channel opening during depolarisation, thus extending the length of Phase 0 and slowing cardiomyocyte action potentials to a further extent than quinidine.

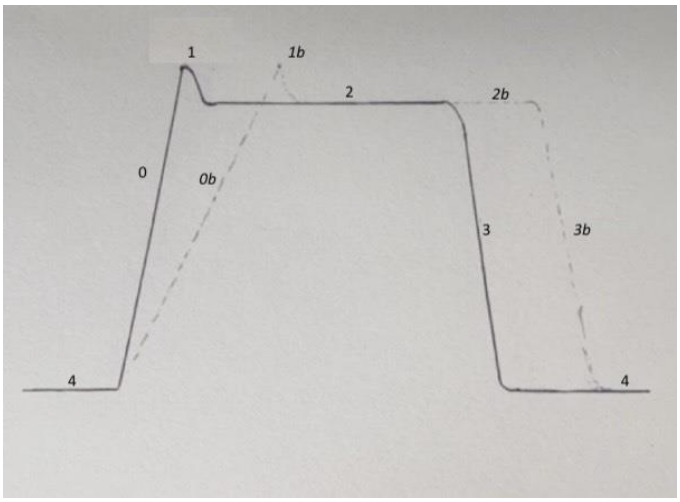

Figure 5: Image showing the effect of flecainide (0b-3b) as seen on a typical cardiomyocyte action potential.

Many studies in the past thirty years have shown that intravenous administration of flecainide can successfully treat horses for acute atrial fibrillations and return sinus rhythm to normal [78] [79]. Takahashi et al [80] studied the effects of flecainide vs quinidine as a treatment for atrial fibrillations in a group of one hundred and seven Thoroughbred horses, finding that only half of the horses successfully converted to sinus rhythm alone compared with 91% with quinidine and 81% with both drugs used. In their study on atrial fibrillation treatment of horses, van Loon et al [81] found that no horses with chronic atrial fibrillations responded to flecainide treatment, indicating its potency only for acute cases. Robinson & Feary [82] studied the cause of sudden death in two racehorses and found that they had been administered oral flecainide after unsuccessful quinidine treatment, showing that there can also be deadly side effects and consequences to flecainide treatment through incorrect dosage or administration. Other drugs which can be used to treat atrial fibrillations in horses include procainamide [77] and amiodarone [83] [84] with promising signs shown but neither showing the potency of quinidine or flecainide, so are not efficient alternatives.

4.2.6 Electric Cardioversion: The final commonly used treatment for atrial fibrillations is the usage of electrical cardioversion. Kimberly et al [85] studied the effects of cardioversion on horses with chronic AF, placing a catheter through the jugular vein into the right atrium and pulmonary artery, delivering shock treatment to each patient while under general anaesthetic. They found success in only one of the patients, but saw no side effects, so concluded that is it a realistic alternative to pharmaceuticals. McGurrin et al [86], studied the effects of electrical cardioversion on seventy-two racehorses who experienced singular atrial fibrillations. By using the same surgical approach as Kimberly et al [85], they found that

seventy-one patients were successfully converted back to sinus rhythm. De Cloedt et al [74], had similar thoughts, finding that 95% of horses that suffered from lone atrial fibrillations were successfully returned to sinus rhythm, even when pharmaceutical options were unsuccessful. Amiodarone can often be used to facilitate this cardioversion to reset electrical pacing of contractions. [84] [74]. It is apparent that electric cardioversion is a realistic and effective approach for treating lone atrial fibrillations, however it is important to determine whether AFs were recurrent before treatment among other factors [87] such as catheter type and electrical voltage used, as recurrence rate after conversion can be as high as 35%.

De Cloedt et al [88] followed up on the recovery of horses seven weeks after electric cardioversion and found that many horses continued to have recurrent atrial fibrillations. Using echocardiography, they found that the horses begun to show signs of recovery, but the horses with larger left atrium sizes were the ones that showed continued AF episodes. In a later 2015 study, De Cloedt et al [62] found that evidence of decreased left atrial fractional change, indicating decreased blood pumped from the atrium during systole, was a reliable parameter of predicting recurrent atrial fibrillations. This it would indicate the need for the heart to compensate with increased heart rate and so increase the likeliness of arrhythmogenic behaviour. Like with Vernemmen et al [87], De Cloedt et al found recurrent episodes in a third of all horses following treatment. De Clercq et al [89] studied the length of atrial fibrillation cycles in horses with recurrent episodes after electric cardioversion and compared them with a group who maintained sinus rhythm fully after treatment. They found that horses with a shorter atrial fibrillation cycle length, as well as larger left atrial size, to both be accurate parameters for predicting AF recurrence. Seeing as Thoroughbreds have relatively larger left atrial sizes than most other breeds, it is clear why AF recurrence is such a problem with the breed and why it is not always clear which treatment is optional for each case. Recent procedures such as ablation [90]; the surgical scarring of tissue to help limit conduction, and cryobaloon ablation [91] have been used to successfully treat humans with recurrent AF, however there is no real research currently of these procedures with horses, likely because of the high cost of surgery.

4.3 Exercise Induced Pulmonary Haemorrhage

Another cardiac disease that can be seen in Thoroughbred horses and other racehorse breeds is exercise induced pulmonary haemorrhage, or EIPH. As mentioned earlier, there is a huge increase in cardiopulmonary flow during exercise, partly due to the huge splenic reserve and

increased demand for oxygen placed on the lungs and pulmonary vessels. Bernard et al [92], studied the redistribution of blood in the Thoroughbred horse at differing exercise intensities compared with rest and found that 70% of blood flow redistribution matches the mean flow with increased exercise, however the additional 30% was mostly going to the dorsal regions of the lung and so adding additional pressure to the vessels in that area. Manohar & Goetz [93], studied the varying pressure differences between horses suspected with EIPH and those who were not, finding the magnitude of pulmonary pressure in both groups to be significantly higher during exercise and no real difference in pressure seen between the two groups, indicating EIPH is able to occur with any horse at high intensities depending on other factors.

Development of EIPH is likely to have several processes involved that cause haemorrhaging in the Thoroughbred. Fedde & Erikson [55] studied the blood viscosity after exercise from a group of forty-nine Thoroughbred racehorses. As discussed earlier, the PCV goes up significantly in Thoroughbred racehorses during exercise, however this larger volume of RBCs increases the shear rate of blood flow and doubles what they call the “apparent viscosity” of blood. Any increase in shear rate directly correlates with an increase on the shear pressure put on blood vessels, adding further to the pressure seen from increased blood flow alone. Angiogenesis and venous remodelling occur frequently in Thoroughbred racehorses as part of long-term compensating for these huge rises in pressure during intense exercise and to tolerate the increased blood flow shear rates [94]. Williams et al studied the anatomical vessel mapping in Thoroughbred horses suffering from EIPH and compared them with a control sample. Venous remodelling was most apparent in the dorsal parts of the lung in the diseased horses, correlating directly with the area seeing the largest change to blood flow in exercise, and this also led to scarring in the form of interstitial fibrosis (IF) during prolonged periods without treatment, with increased IF seen in the horses who had the most progressed forms of EIPH. The literature suggests that large periods of strenuous exercise can lead to EIPH development, and the haemorrhaging will intensify further the longer it goes untreated.

Kindig et al [95], found that exercise induced pulmonary haemorrhages are seen more frequently in strenuous exercise that involves inclined running. The frequent changes in respiratory rates that are naturally seen in athletes during periods of inclined running leads to changes in pulmonary pressures during each inspiration and expiration, and the changes in lung volume leads to more further bleeding. While they found that the highest pulmonary pressures measured during intense inclined training were lower than in flat racing, the large

swings in pressure directly correlated with EIPH intensity, indicating how some nonvascular factors are involved with EIPH development and severity of the disease seen.

Treatment for EIPH is directed towards limiting the rise of pressure during strenuous exercise and historically furosemide has been used as a diuretic to lower plasma volume and thus decrease blood volume. Gleed et al [96], found that administration of furosemide to horses before inclined training led to decreased capillary pressure in the lungs, compared to pressure with no treatment, without also impacting pulmonary arterial pressure or heart rate. The lower peak in capillary pressure was seen with less fluid volume in the lungs and thus lowering the risk of haemorrhaging. Treating the pulmonary hypertension with a diuretic before intense exercise, where we already see a huge rise in PCV and apparent viscosity, is naturally hugely controversial, as there will be a serious risk of clotting and further cardiovascular complications, which has led to the usage of furosemide to treat EIPH to be banned in many countries and racing administrations. Other forms of treatments are not well studied yet, however Erikson et al [97] reviewed a few different methods. The usage of nasal strips increases nasal breathing during exercise, and so lessens the changes of pulmonary pressure seen between inspiration and expiration. Concentrated equine serum reduces the red blood cell count, while small volumes of nitric oxide help reduce overall vascular pressure. Some evidence is also seen for lower development of EIPH seen in Thoroughbreds who have a diet high in omega-3 fatty acids, which have anti-inflammatory properties and help improve general haemodynamics.

4.4 Sudden Death

The third performance-based abnormality affecting Thoroughbred horses, and of course the most serious one, is sudden death syndrome. Sudden death syndrome in horses can be described as the occurrence of a lethal cardiac arrest without any directly known cause, and it is of greatest concern in the world of horse racing. The Irish racehorse Best Mate, a renowned Thoroughbred who won fourteen races from twenty-one starts and the first horse to win three Gold Cups in a row since Arkle, succumbed to sudden death syndrome in 2005 [98]. The owners knew that “once they saw his legs wobble and begin to fall, they knew in that moment he was dead”, however they had no concern for his health before the race, with a then-treated blood vessel the only blotch on an otherwise impeccable medical history. It was afterwards confirmed to be a cardiac arrest, the cause of which remained unknown like many other cases in horse racing today. Historically speaking, sudden death in racehorses is estimated at around

one horse in every ten thousand, with Lyle et al [99] finding that the risk of sudden death in racehorses to be almost ten times larger in jump racing that in flat racing. The proportion dying from sudden death in flat racing is also almost ten times larger than in jump racing, however that is due to the significantly high number of musculoskeletal injuries and related deaths that are seen following jumping and hurdles. According to Diab et al [100], most sudden death cases require toxicology and histology tests as no gross legions are present to indicate direct cause of cardiac arrest, and that standard autopsy procedures are essential to evaluate the causes during post-mortem, look for indications of disease before cases occur and to thus treat horses for any underlying conditions which are currently going undiagnosed.

Bennet & Parkin [101] attempted to identify the risk factors involved in Thoroughbred sudden death in USA and Canada and found fifteen risk factors. Amongst these included the season; with increased cases seen during Northern hemisphere summers when the temperature is higher, the sex; with a slight increase in cases seen involving males compared with female athletes, race length, with longer distances generally seeing less cases, detraining; with horses having significantly higher risk if they experienced large periods of rest during detraining and horses more likely to encounter problems in their first race of the season compared to later in the racing calendar, and age; with older horses having a greater risk than horses below five years old. Nath et al [102] also studied the risk factors involved using data from Southern Hemisphere athletes and concluded that there is a higher risk of sudden death during training compared to racing, while interestingly also finding exercise intensity to have no real correlation to increased risk.

While previous understanding that sudden death is normally caused by burst aortic vessels has since been quashed (only now attributed to less than 1% of cases) and there are still many cases of sudden death left unsolved, a growing number of studies and research suggests that atrial fibrillations and exercise induced pulmonary haemorrhages have roles to play in sudden death syndrome. In their research on post-mortem examinations of sudden death in Thoroughbreds, Kiryu et al [103] found that many horses showed muscle fibrosis in the right atrium near to the SA node, indicating arrhythmogenic scarring. There were also many cases of fibrosis of cardiac muscle near to the AV node too, as well as arteriosclerosis of all nearby blood vessels. Their results indicated that arrhythmogenic behaviour had manifested into scarring and likely indicated undiagnosed history of atrial fibrillations. Lyle et al [99] found that upon examinations of histology in post-mortem, many cases showed signs of haemorrhaging both in the heart and in the lungs and stated that the introduction of more

frequent ante-mortem checks and reports on horses would likely show more atrial fibrillation related activity preceding sudden death, due to it being a functional pathophysiological event rather than structural one.

The pharmacological treatment of atrial fibrillations and EIPH also have some link with sudden death in Thoroughbreds. Robinson & Feary [82] studied a few sudden deaths following the use of flecainide in Thoroughbreds as an unsuccessful treatment for atrial fibrillations, while in their study of treatment for atrial fibrillations in Thoroughbreds, Takahashi et al [80] also had sudden death in a patient following unsuccessful quinidine treatment. These may be a few isolated cases of sudden death caused by pharmacological atrial fibrillation treatment, however sudden death following furosemide treatment has been explored more greatly. Amongst the risk factors involved in sudden death, history of furosemide treatment was the greatest involved, finding that horses treated for EIPH with furosemide had a 66% greater chance of sudden death than those who did not. Loving [104] concludes that when furosemide is used as a diuretic to lower pressure, the excretion of elements such as potassium and sodium in this increased urine can alter the electrolyte balance enough to further upset electrical impulses and start an arrhythmogenic chain reaction culminating in sudden death. The research shows that not only is sudden death not fully understood well enough as a performance-based abnormality, but increased care and understanding is needed in the treatment of other abnormalities to prevent cardiovascular disease escalating further.

5 Conclusion

5.1 Summary

The literature shows why the cardiovascular system of the Irish Thoroughbred makes it such a phenomenal athlete when compared to human athletes and to other racehorses. The large heart size in relation to its body, the ability to greatly increase cardiac output during exercise and the capability to call upon such an enormous splenic reserve are some of the reasons that the average Thoroughbred horse is seen as the perfect equine athlete and goes some way to explaining the success of Irish racehorses such as Arkle, Sea the Stars and Dawn Run to name a few. The literature also makes it very clear however that if training and racing conditions are unfavourable and put enough strain on the cardiovascular system, abnormalities such as atrial fibrillations, EIPH and sudden death can occur. RTE reported Irish racehorse fatalities as one hundred and seven athletes from almost thirty-five thousand runners [105] in 2023 and the

percentage of Thoroughbreds dying during racing averaging at around 0.3% in the past decade, with over one thousand horses dying on the track. While many of these fatalities can likely be credited to musculoskeletal injuries, many injuries and deaths are caused by performance-based cardiovascular abnormalities.

Not only can these abnormalities develop from overcompensation by the cardiomyocytes conducting system and the pulmonary vessels, but older treatments such as quinidine and furosemide may cause more adverse effects to the horse without fully treating the initial problems. This highlights the immediate concern for more prudent treatments and therapies for racehorses if they are to continue racing and earning. It is of great importance ethically to greatly decrease the number of injuries and deaths towards zero. It is also important financially for owners and trainers to ensure that these abnormalities do not occur in the first place through proactive measures, rather than reactive ones, and the literature suggests that this approach is being used more often today.

5.2 Management Based Treatment & Therapy

Human endurance athletes will often perform long distance training at a designated heart rate (usually around 50% max for any individual) in their chosen discipline to build up aerobic fitness and use basic heart rate monitors to ensure the pace is kept steady, rather than average speed or average wattage. The use of heart rate monitors is being used more frequently in training of racehorses, as discussed by Mott et al [106], in which they study the usage of the V800 brand and the Actiheart 5 brand to measure heart rate variability, and by Schrurs et al [107], who studied the usage of the Equimetre brand. The Equimetre has proven to be a popular brand, as it able to measure heart rate during exercise and importantly can also measure recovery parameters, which can help to indicate if the horse is getting adequate rest or if arrhythmogenic behaviour is occurring during heart rate compensation for intense workloads. The Equimetre also has a GPS system for tracking horses in real time and can give trainers both locomotion and stride data. This is crucial data for trainers in order to be able to push athletes during training without causing cardiovascular parameters to leave the physiological range. Through regular and routine collection of this data, this can also help to further research on the effect of different climate, weather conditions and types of surfaces used on heart rate and other parameters, which may help further our understanding on the development of cardiovascular abnormalities and the risk factors involved.

The integration of hydrotherapy for horses to training programmes in recent years has become increasingly popular in Ireland [108]. By regularly using water treadmills and walkers, performance of athletes is increased as they must work harder to break the resistance of the water and so adapt better to the similar stress seen during strenuous exercise or racing [109]. The water temperature allows for more efficient thermoregulation, heart rate does not need to rise to match the workload and there is less of a change in pulmonary pressure due to the pressure put on the thorax when submerged in water, showing how hydrotherapy can be useful for limiting development of both atrial fibrillations and exercise induced pulmonary haemorrhages.

Other methods and programs have been put in place to also reduce the risk of cardiovascular abnormalities as well as other injuries or deaths. Katz et al [110] studied the application of inspiratory muscle training on Thoroughbreds during detraining, a method of maintaining muscle strength whilst not training and so decreasing both the load on the pulmonary vessels when training resumes, whilst decreasing the risk of sudden death on a return to racing. Mukai et al [111] found that through studying the effects of different exercise intensities during detraining, a minimum threshold can be calculated for each athlete to maintain aerobic training capacity and reduce the risk of abnormalities developing on return to regular training. Regular warm-up exercises before intense racing [112] will increase aerobic threshold of the horse and so improve the ability of the athlete to maintain physiological cardiovascular parameters for longer distances.

5.3 Thoroughbred Welfare in Ireland

The Irish Thoroughbred Welfare Council was formed in 2020 by Horse Racing Ireland [113] and the following year established a program involving breeders, trainers, owners, jockeys and stable staff to form four main principles of Thoroughbred welfare; good feeding and good housing followed by good health and good wellbeing, the latter of which involves behaviour, exercise and social interactions. Through establishing and expanding on these principles, the aim of the council is to have each operation form a routine checklist for all parameters under these principles, allowing for Ireland to continue to have horses performing successfully and maintaining its reputation, whilst also ensuring good wellbeing of each horse. As part of the principle of wellbeing, each athlete should have its own tailored exercise plan, with daily feedback from the jockeys recorded and evaluation of any/all increases and decreases to performance in order to maintain good health. By strictly adhering to these principles, and

with good feedback from each organisation, this should allow for increased literature in Irish Thoroughbred exercise physiology and cardiology and will hopefully see a profound drop in performance-based abnormalities going forward.

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Up the Shams ☘

UNIVERSITY OF VETERINARY MEDICINE, BUDAPEST
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Thesis progress report for veterinary students

Name of student: Kevin Fallon

Neptun code of the student: LZPQZM

Name and title of the supervisor: Istvan Toth, Associate professor

Department: Department of Physiology of Biochemistry

Thesis title: Equine Exercise Physiology: A Literature review on the cardiology of the racehorse & performance-based abnormalities

Consultation – 1st semester

	Timing			Topic / Remarks of the supervisor	Signature of the supervisor
	year	month	day		
1.	2023	02	15	The importance of the thesis and consultation; Overview of semester assignments; Preparation and signing of necessary documents	Tóth
2.	2023	03	15	Scientific search engines and their use; Critical thinking: how to interpret the information read in the article	Tóth
3.	2023	04	18	Preparing your first draft	Tóth
4.	2023	05	18	Interpretation and management of scientific citations; Learning the citation handling program	Tóth
5.	203	06	30	By the end of the semester, structure of the thesis and foundations of each chapter are complete	Tóth

Grade achieved at the end of the first semester: 4

Consultation – 2nd semester

	Timing			Topic / Remarks of the supervisor	Signature of the supervisor
	year	month	day		

1.	2023	09	10	Evaluation of the current version prepared during summer	Tóth
2.	2023	09	30	Incorporation of the supervisor's suggestions, and evaluation of final text cohesion	Tóth
3.	2023	10	15	Insertion of final figures and figure captions; review and final update of references, bibliography	Tóth
4.	2023	10	30	Final check: Detection and correction of possible errors	Tóth
5.	2023	11	06	Generate a PDF and review the final PDF before uploading	Tóth

Grade achieved at the end of the second semester: 5

The thesis meets the requirements of the Study and Examination Rules of the University and the Guide to Thesis Writing.

I accept the thesis and found suitable to defence,

Tóth

.....
signature of the supervisor

Signature of the student: .....

Signature of the secretary of the department: .....

Date of handing the thesis in: 2023. 11. 13.

I hereby confirm that I am familiar with the content of the thesis entitled:

"Equine Exercise Physiology: A Literature Review on the Cardiology of the Racehorse & Performance-based Abnormalities"

Written by **Kevin Fallon** (student name) which I deem suitable for submission and defence.

Date: Budapest 14. day 11. month 2023. Year

Supervisor name and signature:

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Department:

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