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REVIEW PAPERS

LEAD IN GAME BIRD MEAT AS A RISK TO PUBLIC HEALTH: NEW ASPECTS IN THE LIGHT OF PHYSICAL PHENOMENA GENERATED BY A PROJECTILE

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Abstract

Annually, hunters shoot millions of birds with lead ammunition. Many studies indicate diverse and often very high lead levels in the edible parts of game. Considering the number of hunters, the determined levels may pose a public health risk. Shotgun pellets are the main source of lead contamination of game animal tissues. Despite numerous studies indicating lead contamination in game birds, no significant reasons for diverse contamination of tissues with this toxic metal have been reported. The analysis presented in this paper suggests that the explanation for diverse levels of contamination of game animal tissues should be sought in physical phenomena generated by a projectile in damaged animal tissues. A projectile penetrating a target generates a multi-phase medium from destroyed tissues and simultaneously changes the shape of its front part. This movement of a projectile is an example of a turbulent flow. The interpretation of the interaction between a projectile and damaged tissues indicate that the variable and unpredictable parameters of a projectile for each shot and the medium created by a projectile make it impossible to determine the degree of this interaction. The phenomenon of a temporary cavity created by a shot seems to determine the magnitude of lead transfer into

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tissues surrounding the path of a wound. Fluid mechanics also explains the relatively high lead levels in game birds in comparison with the levels determined in big game animals. In view of the unpredictability of projectile-animal body interactions, it should be assumed that game bird shot with lead pellets contains the lead levels dangerous to human health. Therefore, the use of lead pellets for bird shooting should be banned.

Keywords: lead, ammunition, birds, hunting, gunshot wounds, temporary cavity, public health.

INTRODUCTION

Hunting remains a specific type of human activity involving the use of lead-containing ammunition, which presents a long-term risk to the health of venison consumers. This health risk phenomenon has been prominently observed among hunters and their families. In Europe, the number of hunters is approximately 7,000,000. Considering hunters' families and friends, it is assumed that game birds are consumed by at least several million persons annually in Europe (Mustin et al. 2012, FACE 2015).

Lead is still the main raw material used to manufacture hunting ammunition. However, in the USA, Canada and occasionally in Europe, it has been replaced with other materials. (Mitchell et al. 2001*a*,*b*,*c*, Thomas, Guitart 2010, Haig et al. 2014, Mateo et al. 2014). Each animal shot with lead projectiles has lead contaminated tissues (Dobrowolska, Melosik 2008, Tsuji et al. 2008, 2009, Knott et al. 2010, Pain et al. 2010, Szkoda et al. 2012, 2013, Mateo et al. 2014). In some cases, the level of lead in muscles is so high that such food presents a direct risk to the consumer health (*Commission Regulation...* 2001, Johansen et al. 2004, Taggart et al. 2011, Ferreyra et al. 2014, Kim, Oh 2014, Lazarus et al. 2014, Felsmann, Szarek 2015).

Theory

Adverse impact of lead used for game bird hunting on the environment and human health

There are numerous studies that have confirmed the adverse impact of hunting with lead shotgun pellets on the environment (Szarek et al. 2001, Bjerregaard et al. 2004, Haig et al. 2004, Iqbal et al. 2009, Felsmann et al. 2010, Thomas, Guitart 2010, Taggart et al. 2011, Mustin et al. 2012, Binkowski et al. 2013, Ferreyra et al. 2014, Kim, Oh 2014, Lazarus et al. 2014, Mateo et al. 2014, Binkowski, Sawicka-Kapusta 2015*a*,*b*, Felsmann, Szarek 2015).

The diversification of lead pollution in areas where migratory birds reside, effects upon the avian organism and the level of metals in the tissues and organs of individual birds have been reported in many studies (Szarek et al. 2001, Bjerregaard et al. 2004, Binkowski et al. 2013, Ferreyra et al. 2014, Lazarus et al. 2014, Binkowski, Sawicka-Kapusta 2015*a*,*b*, Felsmann, Szarek 2015). In areas where birds are hunted with lead pellet, the type of ammunition largely determines the level of this metal in avian tissues (Bjerregaard et al. 2004, Johansen et al. 2004, Tsuji et al. 2008, Ferreyra et al. 2014, Haig et al. 2014, Felsmann, Szarek 2015).

The aforementioned studies indicate that game birds obtained by shooting often contain toxic contaminations at levels posing a risk to humans who consume their meat (Hanning et al. 2003, Bjerregaard et al. 2004, Johansen et al. 2006, Mateo et al. 2007, Dobrowolska, Melosik 2008, Tsuji et al. 2008, Iqbal et al. 2009, Tsuji et al. 2009, Knott et al. 2010, Pain et al. 2010, Mateo et al. 2011, Szkoda et al. 2011, EFSA 2012, Szkoda et al. 2012, Meltzer et al. 2013, Szkoda et al. 2013, Mateo et al. 2014).

The negative impact of lead on living organisms has been well-proven (Tong et. al. 2000, Carpenter et al. 2001, Carlisle et al. 2009, Chandramouli et. al. 2009, Schnaas et al. 2009 Jakubowski 2011, EFSA 2012, Haig et al. 2014, Kim, Oh 2014). The toxic effect of this element has been particularly observed in higher animals (Tong et. al. 2000, Carpenter et al. 2001, Carlisle et al. 2009, Schnaas et al. 2009, Jakubowski 2011). In humans, children are most exposed to intoxication and for them even a small amounts of lead may lead to cognitive disturbances and learning disorders (Tong et. al. 2000, Hanning et al. 2003, Carlisle et al. 2009, Chandramouli et. al. 2009, Schnaas et al. 2009, Jakubowski 2011). In addition, differences in the toxicity of this metal, including exposure time and dose magnitue, should also be considered (Johansen et al. 2004, Johansen 2006, Iqbal et al. 2009, Smolders et al. 2010, EFSA 2012).

RESULTS

Personal observations and remarks

Referring to Felsmann et al. (2012, 2014), the authors performed an analysis of the potential for lead transfer from hunting projectiles into the penetrated tissues and organs based on the physical phenomena generated during a shot. Single projectiles for rifled guns are expected to increase their frontal surface during target penetration (the so-called "mushrooming" effect). Shotgun pellets, which are small balls made of soft metal (Pb), are also subjected to a variable degree of physical distortions when hitting a living target. Their construction makes lead projectiles particularly prone to deformation of their frontal part (Felsmann et al. 2012, 2014).

A projectile that hits a living target causes the piling of tissues present in front of it. The destructive effect of the frontal part of a projectile generates a multi-phase medium from the destroyed tissue and body fluids. The projectile penetrating the tissues moves within this medium. Simultaneously, behind the frontal part of a projectile an area of disturbed flows is formed as a result of its movement and the interaction of elements of the multi-phase medium (Felsmann et al. 2012). The generated chaotic and intensified movement of the conglomerate of body fluids, damaged tissues, gases and (sometimes) detaching fragments of a projectile results in the rapid dispersion of energy carried by these elements. Energy is transferred into the tissues around the path of a wound, which causes its displacement outside of the axis of the projectile's movement, although the volume of energy varies and is typical of only a single shot. In elastic tissues, displaced layers re-collapse and then move outward. This pulsating displacement of tissues around the trajectory of a projectile forms a temporary cavity. The cascading piling of tissues, as a result of their relatively high inertia, still takes place after a projectile has moved, sometimes over a substantial distance (Felsmann et al. 2012).

A temporary cavity is a complex phenomenon and its formation (volume) mainly depends on the momentary shape of the frontal part of a projectile. The surrounding of objects even by single-phase media is always a very complex phenomenon. Each object moving within a fluid or each object flown round by a fluid is exposed to two forces: one is perpendicular to the flow velocity vector (lift force) and the other one is opposite to the flow velocity vector (profile drag) (Felsmann et al. 2012). In reality, only the profile drag force acts on a projectile that penetrates the tissues; the profile drag is the sum of frictional drag and pressure drag (Felsmann et al. 2012). In the case of non-aerodynamic profiles or turbulent (disturbed) flows, theoretical predictions are impossible. Most turbulent flows in multi-phase media are so complex that they are unpredictable (Felsmann et al. 2012).

Hunting projectiles are constructed in a way that enables transferring their energy to the highest extent possible into the body of an animal and this requires that the projectile assumes a shape that destroys the greatest mass of tissues possible. Such construction of projectiles (including pellets) always causes turbulent flow in a multi-phase medium. The time and extent of projectile deformations during penetration of a living target remain unknown. The extent of such distortions seems to be decisive for the amount of lead transferred from a projectile onto the tissues around a wound, and the volume of a temporary cavity is one of the main factors that enables lead transfer into deeper layers around the path of a wound.

Each specific flow around a body is assigned certain values (Reynolds number – Re and critical Reynolds number - Re_{kr}) which indicate the type of flow. The elements of a fluid in turbulent movement usually displace in the direction of mass transport and simultaneously perform pulsating movements in all potential directions (Felsmann et al. 2012). For the objects with non-streamline profiles, such as a distorted projectile or pellets, travelling at velocities comparable to the velocity of hunting projectiles, a boundary layer is always separated. This property results in projectiles moving in a turbulent manner within a multi-phase medium made of destroyed tissues while penetrating a living target.

A disturbed flow is most potentiated during perpendicular flow around flat, sharp-edged profiles and the front part of each hunting projectile may momentarily take such shape (FELSMANN et al. 2012). In reality, the front part of a projectile may assume different shapes: from conical at entering the target, to flat, or even concave, at the terminal stage of penetration, although this momentary shape is always varied and undeterminable. In the case of a pellet, the front shape changes from a spherical to a flat, or even concave, disc and is difficult to predict (FELSMANN et al. 2012).

While interpreting the projectile–living target interaction, selected parameters of fluid mechanics should be considered. The profile drag R_x is the most important one. This is the sum of friction drag R_{xt} and pressure drag R_{xc}. Although the profile drag may be analysed without divisions into elements at no detriment to this elucidation, the authors, based on personal experience, will refer to these elements.

The friction drag R_{xt} is the most important factor for possible detachment of lead chips from a projectile:

$$R_{xt} = c_{xt} A \frac{\rho v_{\infty}^{2}}{2},$$

where:

A – stands for conventional reference surface (momentary surface of the frontal part of a projectile), ρ – fluid density (a multi-phase medium formed by destroyed tissues), v_{∞} – velocity of undisturbed flow (the average velocity of a projectile during target penetration), c_{xt} – friction drag coefficient (an experimentally determined parameter that is impossible to measure for a specific shot).

The friction drag coefficient (c_{xt}) is difficult to determine theoretically, even for homogenous media. For multi-phase media, this parameter can be determined only experimentally and this is possible in a specific arrangement with constant parameters (FELSMANN et al. 2012). Even flows in single-phase media show varied friction drag coefficients (c_{xt}) for the same Reynolds number (Re); furthermore, the magnitude of this coefficient depends on the roughness of the surface of a flown-round body (Figure 1). As seen, c_{xt} is always significantly higher for turbulent flows, whereas considering the roughness of a flown-round object (a projectile), the value of this coefficient from a certain Reynolds number value remains constant and very high. The value of the Reynolds number increases together with increments of flow-round velocity (projectile velocity) and the surface of a hunting projectile, which – even if not rough initially – becomes such while penetrating a target. It should be emphasized that roughness applies to structures on a micro scale and not only to macroscopic surfaces. The movement of a projectile in the multi-phase medium it creates runs in a disturbed manner (turbulently) as depicted in Figure 1 (a single continuous line). Therefore, as the velocity decreases, the frictional drag coefficient of projectile movement may increase. If the surface

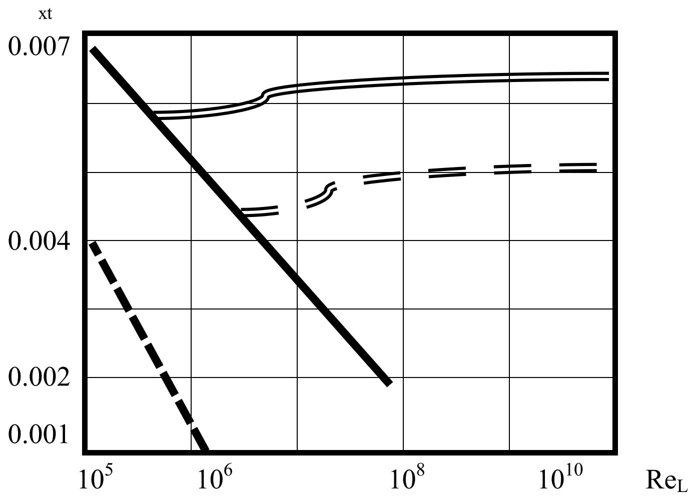

Fig. 1. Example of a change in the friction drag coefficient as a function of the Reynolds number for a flat plate $\{c_{xt} = f(Re_L)\}$ in different types of flow, including the impact of roughness. Laminar flow: dotted line. Turbulent flow: continuous line. The impact of the same absolute roughness in turbulent flow: double lines (continuous for a shorter plate and dotted for a longer plate)

of a flow round object is rough, as in most projectiles (especially in pellets), this factor should be included when the movement of a projectile is considered (Figure 1, double lines) due to the fact that the frictional drag coefficient for rough objects remains high and constant regardless of the increasing Reynolds number value. In reality, rough projectiles may generate higher frictional coefficients regardless of their velocity and, as such, they permit higher lead transfer into the tissues of a shot animal. In addition, with the same absolute roughness (the surface on non-shielded lead elements), higher friction drag coefficient will be generated by shorter projectiles (with a smaller length-to-diameter ratio), such as pellets used for bird hunting (Figure 1, a double continuous line). In the light of these dependences, it becomes clear why such diverse and sometimes high lead levels are found in avian tissues.

It seems that the pressure drag R_{xc} is less important for the detachment of lead chips from the surface of a projectile. However, the impact of this factor is clearly more important for the transfer of detached Pb particles into the tissues surrounding the path of a wound. Although when considering the complexity of turbulent flows in multi-phase media, this assumption is only a hypothesis expressed with the following formula of a relationship:

$$R_{xc} = c_{xc} A \frac{\rho v_{\infty}^{2}}{2},$$

where:

A, ρ, v_∞ denote the same parameters as for R_{xt} and c_{xt} is pressure drag coefficient (an experimentally determined parameter which is impossible to measure for a specific shot).

Similarly to the frictional drag coefficient (c_{xt}), it is impossible to determine the pressure drag coefficient (C_{xc}) for a specific shot due to multiple factors and time-changing value of parameters. The coefficients of frictional drag and pressure drag also depend on the shape of a flown round object, its location in reference to the flow vector as well as the Reynolds and Mach numbers, though the latter may be omitted in the Ma < 0.4 range (Felsmann et al. 2012).

In order to facilitate the understanding of the nature of turbulent flows, we list the factors that influence the Reynolds number and Re (Felsmann et al. 2012).

$$\mathrm{Re} = \frac{\rho v D}{\mu},$$

where:

ρ stands for fluid density, v – velocity of undisturbed flow, D – dimension typical of a specific object and μ – dynamic viscosity of a specific fluid.

Fluid density (ρ) for multi-phase media is difficult to calculate. In the case of a projectile penetrating the body of an animal, determination of this parameter at a specific moment is virtually impossible. The projectile, while rupturing the tissues and individual anatomic structure, creates a triple-phase medium in front and around itself, in which water is a continuous phase (contained in the blood, lymph, intercellular and intracellular fluid) and solid elements of the tissues and anatomical structures and gases released from damaged tissues constitute a dispersed phase (Felsmann et al. 2012).

Regardless of the construction of a projectile and its velocity, it is impossible to determine the density of a fluid (medium) in which a projectile moves at a specific moment due to the momentary state of the penetrated tissues. In addition, the parameters and properties of such medium vary in time and space and changes occur very rapidly. In the case of a projectile penetrating the body of a living creature, the specific velocity (v) of a fluid equals its velocity. During the penetration, this velocity decreases and the degree of change may fluctuate depending on the interaction with individual fragments of tissues and organs. Furthermore, the trajectory of a projectile may change. At the same time, this interaction (happening in milliseconds) depends on the momentary state of individual organs. For instance, the penetration of a projectile through the lungs depends to a certain extent on inspiration and expiration. Similarly, the penetration through the heart muscle is determined by contraction and relaxation. Inspiration and the cardiac muscle contraction also impact the current state of all tissues (momentary blood supply), which translates into a diverse composition of the multi-phase medium generated by a projectile.

The dimension typical of a flown round object (D) is another parameter that influences the magnitude of the Reynolds number (Felsmann et al. 2012). For a projectile, this is the shape of its frontal part perpendicular to the axis of its trajectory. During penetration, the D value constantly changes.

The dynamic viscosity of a fluid (μ) is the last factor. As mentioned before regarding the density of a fluid (ρ) in which a projectile moves, it is impossible to determine its value. In the case of dynamic fluid viscosity, determination of μ for a specific case is impossible for the same reasons. Thus, it is impossible to determine the Reynolds number for each individual gunshot. This also indicates that it is not possible to determine the friction drag coefficient (c_{xt}), pressure drag coefficient (c_{xc}) and, consequently, the profile drag (c_x). However, it should be noted that the shape of a projectile directly impacts the magnitude of the Reynolds number. The type of the flow round and the size of the temporary cavity implicate these relations.

The formula for profile drag (R_x) includes a component called the conventional reference surface (*A*). This parameter (*A*) is a reflection of the current shape of a projectile and its longitudinal dimension, and it undergoes constant changes during tissue penetration (similar to the magnitude of the profile drag itself). The R_x vector may also change, which thus prevents any prognoses as to the behaviour of a projectile in the animal body.

The presented phenomena of fluid mechanics constitute the basis for evaluating the projectile-animal body interaction. For single hunting projectiles, their distortion during penetration is complex insofar as they are not homogenous (excluding Breneke-type projectiles) (Knott et al. 2010, Felsmann et al. 2014). However, hunters very rarely use FMJ projectiles. In most cases, these are different types of JSP projectiles. Their construction results in their substantial deformation in the animal body, although the external layer (jacket), while being distorted, may reveal the lead core to a different extent. Therefore, the contact of the lead core with the tissues around the trajectory of a projectile depends on the construction of a projectile and the size of jacket distortions. The larger the surface of a projectile core (made of lead) that contacts destroyed tissues and a multi-phase medium formed as a result of penetrated tissue destruction, the higher the potential for detachment of lead chips from a projectile. It should be assumed that there is a relationship between the friction drag coefficient (C_{xt}) and roughness of a projectile (momentary roughness). Since roughness increases the friction drag coefficient, it enables detachment of more lead particles from a projectile.

In view of the above, we conclude that the results reported by Dobrowolska and Melosik (2007), who did not know the types of projectiles used to shoot animals (different ammunition can be used with the same type of gun, Figure 2A), are understandable. Exposure of a part of the core or its complete coverage with jacket elements result in a situation in which the contact

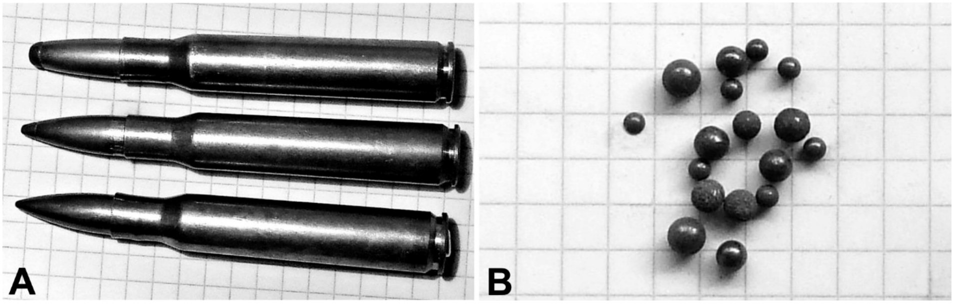

Fig. 2. Lead-containing ammunition used for hunting: A – ammunition for the same type of hunting gun with projectiles with varied tips, B – lead pellets from hunting cartridges (a cartridge contains pellets of the same size). Distance between boxes = 0.5 cm

surface of the core with tissues may be different when hitting a living target while this surface undergoes unpredictable changes during target penetration. Therefore, based on the type and construction of a projectile, it may be assumed that there is potential lead transfer in the direct proximity of a projectile inlet. However, according to the laws of fluid mechanics, it may be impossible to determine the amount of lead that detaches from a projectile and transfers into deeper layers around the path of a wound.

The projectile that penetrates the animal body generates a temporary cavity and this phenomenon is accompanied by a change in the pressure within the funnel of a wound and in the adjacent tissues (Felsmann et al. 2012). This cavity is formed behind a projectile and may persist even after the projectile has left the target. Its size is difficult to predict and the momentary shape of the frontal part of a projectile seems to have a major impact on its formation and size (Felsmann et al. 2012). Due to the temporary cavity phenomenon, especially pressure fluctuations in the tissues where it is found, it may be assumed that this phenomenon is responsible for lead transfer deep into the tissues that surround the path of a wound. The highly variable results of studies on the content of lead at the same distance from the path of a wound in individual animals are unsurprising due to this physical phenomena (Dobrowolska, Melosik 2007).

The increased lead levels in projectiles hitting bones, as reported by other authors, seem to confirm the presented explanation of lead transfer from projectiles to animal tissues. After hitting the bone, a projectile may be fragmented, the core may be exposed and secondary projectiles may be generated. Detached fragments of the projectile core most often move at a different velocity than the projectile (its core part), contaminating a larger area of tissues (Knott et al. 2010). These fragments increase the surface of lead elements that come in contact with the surrounding tissues. Detached projectile fragments and comminuted bone become secondary projectiles that generate a temporary cavity and, although an individual “secondary” temporary cavity may coalesce, it always expands the area of contaminated tissues.

The demonstrated variability of factors responsible for the detachment of lead chips from hunting projectiles and their transfer into tissues adjacent to the trajectory of a projectile explains the diversification of study results on the level of this element in the tissues of shot animals.

The discussed unpredictability of lead contamination in tissues of animals shot with hunting projectiles might be even more variable in bird (small game) hunts where lead pellets are used. In this case, these are lead balls (often rough) forming multiple projectiles (Figure 2B). Considering legal bird hunting, it should be emphasized that pellets most often hit the largest edible part, i.e. breast muscles. An accurate shot results in hitting this group of muscles with at least several lead balls (Figure 3).

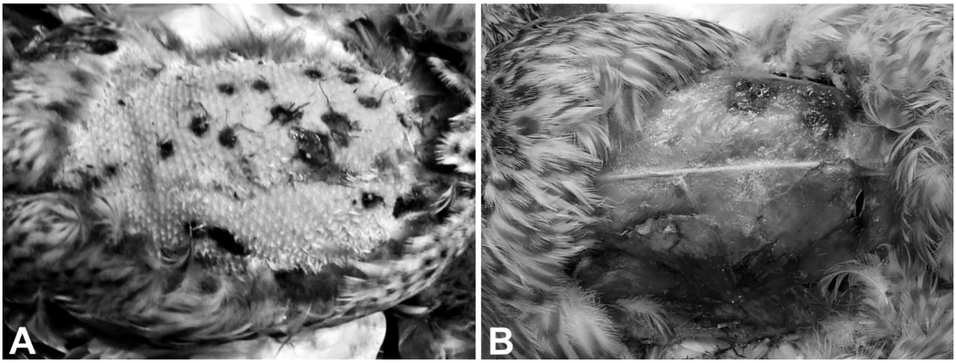

Fig. 3. Wounds inflicted by pellet gunshot in the skin and muscles of mallards: A – several wounds of different sizes in the skin over the breast area, B – wounds in the breast muscles

Each single projectile follows the aforementioned laws of fluid mechanics. When a spherical projectile moves within a multi-phase medium in a turbulent manner, it generates a relatively high friction drag and pressure drag. As a pellet is made of lead, during its turbulent flow many lead chips may detach from its surface and generate a temporary cavity which enables lead transfer deep into muscles. Since the mass and energy of a single pellet projectile (in relation to a hunting bullet) are small, the mass of the detached lead chips and the size of the temporary cavity are also relatively small. However, one should compare the muscle mass of big game (wild boar, red deer or even roe deer) with the muscle mass of game birds. If the fact of several projectiles pitting the small breast muscles is added to these comparisons, the large diversification of lead levels in the muscles of game birds becomes clear.

In addition, considering the destruction of tissues by hunting projectiles, including damage to the blood vessels, it should be remembered that lead chips may penetrate damaged veins and reach distant tissues via this route. This seems only possible with shots that do not kill an animal immediately.

CONCLUSIONS

1. Contamination with lead from lead pellets is a result of a complex process described by the fluid mechanics and the presence of pellets in a carcass.

2. Since each game bird shot with lead pellets should be handled as potentially dangerous to humans, this type of food should be excluded from the human diet.

3. The use of lead pellets in bird hunting should be banned.

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