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Lead-free 22lr ammunition for sport shooting: A simple implementation or a huge challenge?

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Abstract

In Europe it is approximated that around six million people are active in sport shooting. Currently, most bullets are manufactured out of lead which in many cases is combined with a copper jacket. There are several reasons for using lead; lead is relatively cheap, soft, and has a high density, and is therefore often the ideal material for bullets. Currently, the EU is seeking a restriction or ban on the use of lead in firearm bullets, with the main motivation that hunting with lead bullets might result in lead poisoning of both animals and people. The proposed lead ban will also have a major impact on sport shooting, as it is likely to be subjected to the same regulations. One caliber that has been shown to be very difficult to produce as a lead-free alternative is 22lr (long rifle), which today is the most common caliber for sport shooting in many disciplines. Today, there are not many scientific investigations available which show the performance of lead versus lead-free ammunition in caliber 22lr, even though it would make sense to investigate the possibilities of designing lead-free ammunition before a possible lead ban is further discussed. In this work the performance of two common lead-free 22lr-cartridges is evaluated and shown in comparison with existing lead-based ammunition, with a primary focus on sport shooting. Performance has been evaluated under both summer and winter conditions to cover different sports shooting disciplines. The results of this study clearly show the difficulty of finding lead-free 22lr cartridges with acceptable performance on the market today. In fact, the performance of the tested lead-free ammunition is so poor that the EU's proposed lead ban could completely ruin shooting as a sport due to a lack of functioning ammunition.

Keywords

Lead, lead-free, caliber, 22lr, .22, long rifle, ammunition, bullets, biathlon, shooting, shooting sports, accuracy, ballistics, impact, aiming, projectiles, physics of sports

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Introduction

Sport shooting is one of the most popular recreational activities in the world today. In Europe alone, it is approximated that around six million people are active in Sport & Target shooting, based on statistics from 2013.[1,2] Sport shooting activities are performed at shooting ranges, which generally have had the same design for many decades. The shooting ranges are equipped with bullet traps which traditionally are designed as a sand berm or other devices that collect the bullets and their fragments for environmental and/or safety reasons. Most bullets used today are created out of lead which in many cases is combined with a copper jacket, but there are also many bullets that are used without copper jackets, especially in sport shooting. There are several reasons for using lead; lead is relatively cheap, has a high density and is soft, and is therefore many times the ideal material for bullets.

Currently, the EU is seeking a restriction or ban on the use of lead in firearm bullets for sport shooting and hunting due to lead's alleged environmental impact. The evidence that lead from bullets is detrimental to the environment is, however, disputed. It has been shown that lead in the digestive systems of animals could result in lead poisoning, mainly due to the acidic environment in the digestive system. Therefore, lead has been banned in shotgun shells used over wetlands (i.e. hunting) for many years in the majority of European countries, because birds could become lead poisoned if they

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swallow lead pellets from a shotgun.[3] For the same reason, sport shooting with shotguns has already, for many years, often been performed with steel shots.

It is, however, not proven that lead is dangerous or leaks poisonous chemicals at an alarming rate when lying on the ground or in a sand trap. On the contrary, several investigations show that lead from bullets in sand bullet traps[4,5] or lead cables buried in the ground[6] will not lead to any large environmental issues, due to lead's low oxidation rate. Therefore, the lead used at shooting ranges should not be considered harmful to the environment or the biota around the shooting range, and it would be logical that sport shooting should be excluded from the proposed lead ban. That is unfortunately not the case and even if most investigations regarding lead poisoning from ammunition are in fact focused on hunting[3,7–11] the conclusions are often, rather surprisingly, that lead should be banned in all ammunition, *even that* used for sport shooting. Also, most investigations[3,8–11] focus on the environmental aspect of lead poisoning and do not discuss the technical performance of lead-free versus lead ammunition. However, for sport shooting, the performance of the ammunition is the highest priority.

The focus of this article is to evaluate the technical performance of lead-free ammunition in comparison to conventional ammunition, with a focus on caliber 22lr (long rifle) which is the far-most common caliber available for sport shooting in the world. The performance has been evaluated at temperatures of + 22°C and −12°C to show the performance both during summer and winter conditions. The performance during cold conditions is interesting because many sports (e.g. the biathlon) are performed during winter. However, the winter performance has seldom been thoroughly tested in other investigations.

The 22lr cartridge normally consists of a lead bullet and has a muzzle velocity close to the speed of sound in the air. One reason for its popularity is the low cost, which enables a low cost for both training and competition, in combination with high precision at short shooting distances. Most sport shooting with this caliber is performed at up to 50 m, which is the normal distance for many rifle competitions using 22lr (e.g. the biathlon).

Today, there are not many scientific articles available that evaluate the technical performance of lead-free ammunition, and especially in caliber 22lr little has been published in scientific journals. This lack of research is a direct consequence of the fact that there are not many types of lead-free 22lr cartridges available. Two examples of evaluations are the article from McTee and Ramsey,[12] which gives a short comparison of one lead-free 22lr cartridge with a number of lead-based cartridges evaluated in hunting rifles, and Hampton et al.,[7] where the hunting performance of the same type of lead-free ammunition is evaluated. Most ammunition reviews are, however, given in popular science magazines or as video reviews on YouTube. These reviews are, however, limited investigations that should benefit from a more scientific setup where more variables are controlled and evaluated to give a fair comparison of the different types of ammunition.

In this work, the results from testing two lead-free cartridges with their corresponding lead-based alternatives will be discussed in relation to performance, price, and compatibility with existing 22lr rifles, and the results could be referenced when discussing a possible future lead-ban. The performance of the different 22lr cartridges is compared with the target areas used for the biathlon, because the biathlon is possibly the most well-known shooting sport for the general public. The results could, however, also easily be applied to the discussion of the possibility of using lead-free alternatives for other sport shooting disciplines.

The results in this paper show that it is difficult to find acceptable lead-free 22lr cartridges on the market, which is an indication of the difficulties of designing such a cartridge. The cost of lead-free alternatives is also, today, much higher in comparison to lead-based alternatives and the performance is also poor in comparison with lead-based ammunition. In fact, the performance of the tested lead- free ammunition is found to be so poor that it would completely ruin shooting as a sport if a lead ban were to be implemented.

Method

The performance of different ammunition was evaluated at shooting ranges at a distance of 50 m, which is a normal distance for many types of rifle competitions with caliber 22lr, such as the biathlon and short-range rifle. All tests have been performed with the same rifles under various temperatures. Two different bolt-action rifles have been used in the comparison because it is a well-known fact that different ammunition can perform better or worse in different rifles. The shooting procedure is designed to be as fair as possible and not dependent on the order of the different ammunition types, to give results that could easily be compared with each other in a qualitative fashion. Also, to reduce the shooter's influence on the precision of the shots, the rifles have not been operated by a shooter on a normal shooting rest but have instead been mounted in a stable and high-precision test bench where the rifle can be fired without any shooter being directly involved in the aiming and firing. The rifle is simply aimed at the target in the test bench and the firing is done with an external device to ensure that the aiming point, stability, and firing procedure will be exactly the same for all shots. Therefore, the results are not connected to the shooter's ability to aim and fire the rifle and the comparison between the series will be of higher quality than what is possible with a normal shooting rest. Also, when aiming is performed by the shooter through a scope it is not possible to know if the shot is aimed at exactly the same position every time and the aiming position could easily be different, from a few millimeters up to a centimeter or more, depending on the scope and magnification.

During the tests, all the hits were observed through an external high-magnification scope to ensure that no deviant behavior could be observed. Such behavior could for example be if the center of aim moved during the test series or if the spread suddenly increased. Such an observation could indicate a lack of precision in the test bench or that other conditions changed during the test. If such behavior would have been observed the test series would have been aborted. No deviant behavior was, however, observed, and therefore all presented test series could be considered valid. In the series for the ammunition with worse precision, the larger spread was observed to be stochastic and could therefore not be considered as related to any faults in the setup or change of the conditions.

In the field of shooting and ammunition, imperial units are often used. Therefore, sometimes these units are used in this paper, but also complemented with metric units.

Test rifles

The rifles used for the investigation were two bolt-action 22lr rifles; a Ruger American Rimfire Target and a BRNO CZ 457, as described in Table 1. Two rifles were used to ensure that the measured performance is not based on only one individual rifle, because some individual rifles perform better with specific ammunition. The general trends are, however, normally very similar between different rifles, which is also clear from the Results section. That means that for this type of investigation, where only general ammunition performance trends are evaluated, there is no need to involve a large number of different test-rifles.

The Ruger is a factory modified target version of the standard American Rimfire with a heavier, so called, “Varmint” or “Bull” barrel, while the CZ 457 is a standard factory model. The twist rate for both rifles is 1:16″, which could be seen as a standard twist for rifles in caliber 22lr because almost all 22lr rifles have a 1:16″ twist or close to that.

The two rifles are hunting rifles of good standard and condition. There is still, however, a difference in precision between these types of rifles and professional competition rifles such as those used in the biathlon and other 50 m rifle disciplines. The high-end competition rifles are expected to perform better than the rifles used in this study, but they are, however, designed to use the same type of ammunition and they have a similar barrel twist, and therefore the trends seen in this study should be similar for high-precision competition rifles.

Table 1. The rifles used in this test for evaluation of ammunition.

Make	Model	Barrel	Twist
Ruger	American Rimfire Target	Varmint 18″ (406 mm)	1:16″
Brno CZ	457 Synthetic 20″	Standard 20″ (525 mm)	1:16″

Note that the barrel length in inches is not a precise measure (rounded to closest inch), while the measure in mm is more precise.

Tested ammunition

The majority of ammunition available in caliber 22lr is lead-based with a pure lead bullet, or in some cases a copper-plated lead bullet. The term “copper-plated” is used because the copper layer is so thin that it would not be counted as a full copper jacket. The standard bullet weight is 40 grains (2.6 g) and most have a velocity directly at the muzzle, *V0*, of about 1050–1100 fps (320–335 m/s). Cartridges exist with lighter or heavier bullets and lower or higher *V0* for special purposes.

While there is a huge number of different lead-based 22lr ammunition types on the market, there are still only a handful of lead-free alternatives available. What the lead-free cartridges have in common is that the lead-free bullets are lighter than the lead-based bullets and have a higher muzzle velocity, *V0*, to stabilize the bullet and give a higher kinetic energy. In sport shooting it is important to have sufficient kinetic energy when hitting the targets, especially in disciplines using so-called “falling targets” (e.g. the biathlon) at 50 m shooting distance.

In this work two lead-based types of 22lr ammunition were evaluated; one inexpensive type that could be seen as a baseline of how an inexpensive lead-based cartridge could perform (CCI std) and one expensive competition-quality cartridge (Lapua Polar Biathlon) which should be seen as a baseline of the performance of a competition cartridge. These were compared against two lead-free alternatives, both with a cost comparable to the competition-quality cartridge but with totally different bullet technologies: one with a copper-plated zinc bullet (Norma Eco Speed 22) and one with a copper/polymer type of bullet (CCI Copper 22). The four tested cartridges in this work are shown in Figure 1. As clearly shown, there is not a large difference between the two lead-based cartridges, while the lead-free cartridges are different, especially when looking at the bullet.

The aim of the study is therefore clearly not to give a full overview of the performance of all existing ammunition types for the 22lr caliber, but to merely compare the performance between lead-based and lead-free ammunition of different types. All the ammunition was manufactured by well-known manufacturers and is considered to be of high and consistent quality. The specifications of the tested ammunition are showed in Table 2.

Testing procedure

Before the test series were performed, 20 shots with lead ammunition (CCI std) were fired to slightly heat up the

Figure 1. The four different tested 22lr cartridges. From left to right; CCI std, Lapua Polar Biathlon, Norma Eco Speed 22, and CCI Copper 22. Please note that the free bullets in this picture suffer from scratches from the disassembling of the cartridge.

barrel to a steady state temperature and to ensure that no residues of gun oil, etc., were left in the barrel from previous cleaning procedures.

All tests were documented on a target of corrugated cardboard to enable scanning and presenting the results in a clear way.

Extensive pre-testing showed that no large difference in performance could be observed depending on which order the series were shot. However, because the performance of a rifle/ammunition combination potentially could change when switching ammunition type, five shots of the same lead ammunition (CCI std) were always fired between the different types of ammunition to ensure similar starting conditions for each test series. For a clear comparison between the tested temperatures, the series shown in the result section were always shot in the following order: Lapua Polar Biathlon, CCI Copper 22, CCI std, then Norma Eco Speed 22.

The test series were performed at two different air temperatures at an outdoor shooting range and a shooting distance of 50 m.

- First Test Series: + 22°C and a relative air humidity of 65% and a wind speed of < 1 m/s. These conditions could be considered as normal summer conditions. Test series with 25 shots were performed for each ammunition type.
- Second Test Series: −12°C and a relative air humidity of 40% and a wind speed of < 1 m/s. These conditions could be considered as normal, however very mild, winter conditions (representative for the biathlon). Test series with five shots were performed for each ammunition type.

The ammunition was stored at an ambient temperature for a sufficient amount of time to be considered to have the same temperature as the measured air temperature in each test.

Bullet velocity measurement with Labradar

The bullet velocity has been monitored throughout the tests with a Labradar,[13] a ballistic velocity doppler radar which can measure and track the velocity of the bullet throughout the flight between the nozzle and the target. The measured velocity data could be used for investigating several theories of why the spread varies for different ammunition types by using the measured velocities for ballistic calculations. However, the data in this work has been used to:

- Show the muzzle velocity, *V0*, and its standard and extreme deviation for the evaluated test series. The standard and extreme deviation could be seen as parameters that could imply a larger spread at the target.
- Calculate the energy at the target, *E50*, indicating if the cartridge is suitable for activities where the energy at the target is important (e.g. for falling targets such as in the biathlon).

During the velocity measurements, the Labradar device was placed close to the muzzle of the barrel, as shown in Figure 2.

Shooting rig

To enable a scientific comparison between the different ammunition it is of foremost importance to reduce as many variables as possible. Because the shooter would have the largest influence out of all variables it was necessary to eliminate the shooter from the test procedure to make a fair comparison of the ammunition in a

Table 2. Tested ammunition in caliber 22 lr.

Make	Type	Bullet type, weight (g)	Velocity *V0* (fps, (m/s))
CCI	Std	Lead, 40gr	1070, (326)
Lapua	Polar Biathlon	Lead, 40gr	1105, (337)
Norma	Eco Speed 22	Copper plated zinc, 24gr	1706, (520)
CCI	Copper 22	Copper/polymer, 21gr	1850, (564)

Bullet weight and velocity are as given by the manufacturer. The real bullet velocities are given in Tables 3(a) and (b).

Figure 2. Setup with Labradar equipment to enable measurement of bullet velocities. The Labradar is the orange box close to the muzzle of the rifle that is mounted in the rig.

Figure 3. A view over the shooting rig that was developed and used for this investigation.

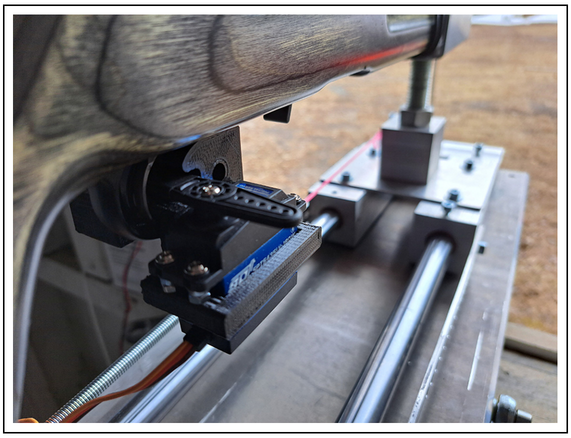

Figure 4. The firing mechanism that enables the shooter to fire the rifle without touching it or its trigger. This rig was developed to ensure consistent firing of all shots and good repeatability.

scientific manner. Therefore, a shooting rig was developed to enable the test shots to be fired without a shooter touching the rifle, except for re-loading due to the use of bolt action rifles in this study. The developed test rig is shown in Figure 3. The rifles were firmly attached to the rig to reduce all movement, except for a recoil-dampening mechanism in the axial direction of the barrel. To enable the perfect firing of every shot the firing is conducted through a developed system featuring a sturdy digital radio control (RC) servo and an Arduino-based control system. This firing device was attached to the trigger guard of the rifle, see Figure 4, and ensured that the rifle was fired with a smooth, steady, and repetitive trigger motion, with slow employment of the trigger, approximately 1 s after the shooter has initiated the shot from the control box. The precision and repeatability of the developed shooting rig could easily be illustrated by looking at the series performed with well-functioning lead-based ammunition under good shooting conditions in Figures 5 and 6.

Ballistics

To ensure good ammunition performance with little spread between different shots it is important to design the cartridge so that it, in combination with the specific weapon in mind, gives good bullet stability. The stability of the bullet is influenced by a large number of variables, such as barrel twist rate, humidity/density/temperature of the air, and the bullet's weight and geometry.

It is normally not so difficult to design a weapon for an existing cartridge because the important properties of the weapon, such as the barrel's expected twist rate, are well-known. However, re-designing a cartridge that will perform well in existing weapons, could be extremely difficult. Especially if certain boundary conditions, such as the bullet's energy at the muzzle or at 100 m must be above a certain value, the re-design could be extra challenging. This complexity might induce various problems when trying to replace lead in bullets for various calibers. Lead is often used in bullet designs because it has many beneficial properties; it has a high density and is soft, ductile, and cheap. These

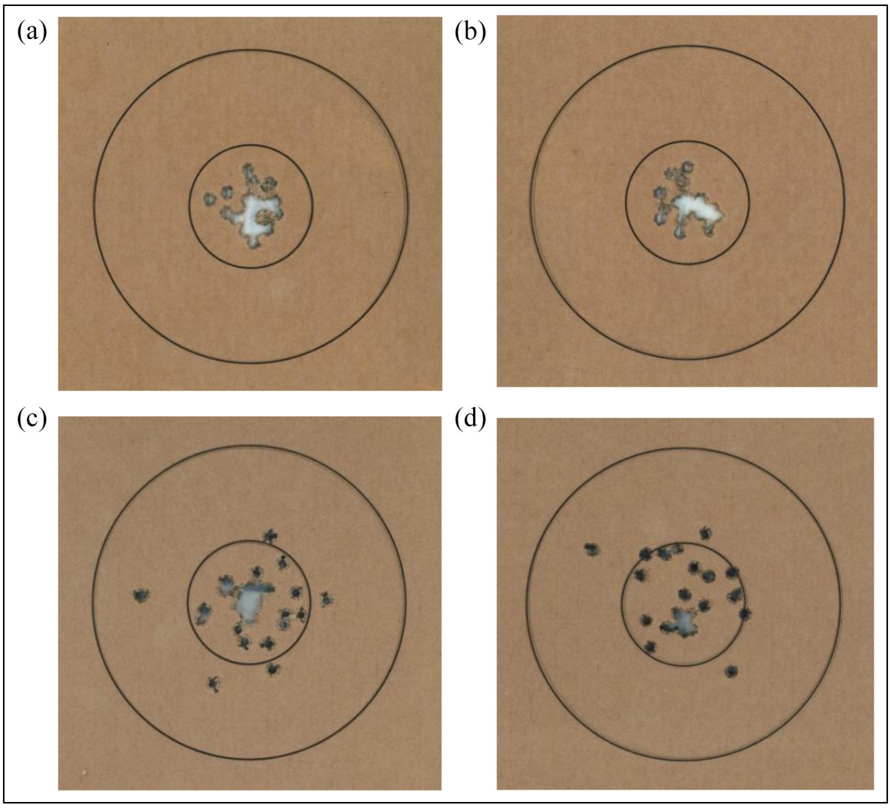

Figure 5. Results from the 25 shots test series at 22°C. The results are shown in relation to the two target sizes in the biathlon, 45 and 115 mm. Test rifle: Ruger American Rimfire Target: (a) CCI std, (b) Lapua Polar biathlon, (c) CCI Copper 22, and (d) Norma ECO Speed 22.

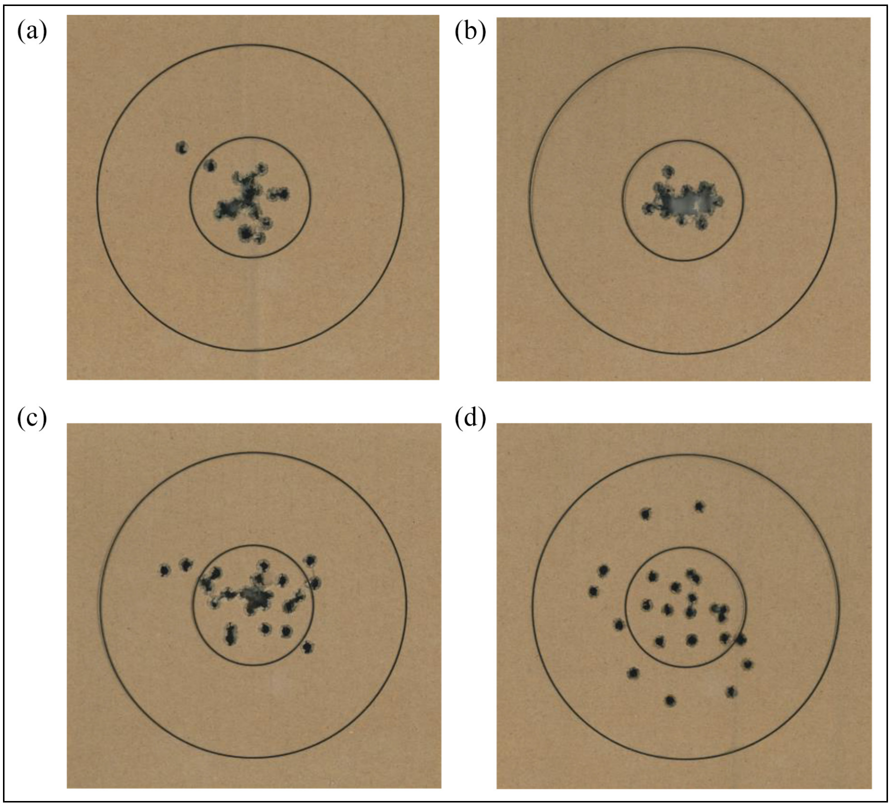

Figure 6. Results from the 25 shots test series at 22°C. The results are shown in relation to the two target sizes in the biathlon, 45 and 115 mm. Test rifle: BRNO CZ 457: (a) CCI std, (b) Lapua Polar biathlon, (c) CCI Copper 22, and (d) Norma ECO Speed 22.

Table 3. Velocity of tested ammunition from a series of 25 shots at 22°C and five shots at −12°C.

(a) Rifle: Ruger American Rimfire Target.

Cartridge	Temp (°C)	*V0* (m/s)	SD (m/s)	EXT (m/s)	V50 (m/s)	E50 (J)
CCI std	22	325	4	14	297	114
Lapua Polar biathlon	22	338	3	10	312	126
CCI Copper 22	22	478	27	72	N/A	N/A
Norma eco speed 22	22	455	10	39	367	105
CCI std	−12	317	3	8	285	105
Lapua Polar biathlon	−12	308	4	9	281	102
CCI Copper 22	−12	392	8	16	N/A	N/A
Norma Eco Speed 22	−12	411	10	24	307	73

(b) Rifle: Brno Cz 457.

Cartridge	Temp (°C)	*V0* (m/s)	SD (m/s)	EXT (m/s)	V50 (m/s)	E50 (J)
CCI std	22	324	4	14	298	115
Lapua Polar biathlon	22	342	2	9	317	130
CCI Copper 22	22	524	25	50	N/A	N/A
Norma Eco Speed 22	22	480	8	38	371	107
CCI std	−12	317	3	8	287	107
Lapua Polar biathlon	−12	315	1	3	287	107
CCI Copper 22	−12	425	13	18	N/A	N/A
Norma Eco Speed 22	−12	452	7	17	355	98

Displayed values are average muzzle velocity (*V0*) with standard deviation (SD) and extreme values (EXT). The average velocity (V50) and energy (E50) at 50 m are also displayed.
CCI Copper 22 gave poor measurements in general and only a few shots gave valid measurements at 50 m. Therefore, no results for V50 and E50 are presented for this cartridge.

properties enable the manufacturers to develop bullets with a high precision that also reduce the wear of the barrel to a minimum. When trying to replace the lead in the bullets with financially acceptable alternate materials, you almost always end up with a material with a lower density than lead. If the same bullet weight is requested, the bullet must become longer, thereby changing the bullet geometry and therefore changing the stability of the bullet. If it is not possible to make the bullet longer, a higher muzzle velocity is needed to retain the muzzle energy, and the higher velocity will, in turn, also influence bullet stability. The difficulty of replacing the lead and still getting an acceptable performance in existing weapons varies between different calibers. In general, high-velocity calibers are easier to design as lead-free, while it is more difficult to design lead-free bullets with acceptable performance for slower calibers, such as .22lr and 32 S&W Long WC.

Results

The results from the test series are divided into two sections; The main results from 25-shots series at an air temperature of + 22°C and the complementary five-shots series at −12°C, to investigate if the trends thoroughly investigated at + 22°C also apply under winter conditions. All results are shown in relation to the target sizes in the biathlon, where the inner ring corresponds to the target size for shooting when lying down (45 mm in diameter) and the large diameter corresponds to the target size for shooting when standing up (115 mm in diameter). An acceptable precision for this type of competition is when the spread of the rifle and ammunition is much smaller than the size of the smaller circle. Otherwise, the skill of the shooter will be less important than the spread of the rifle and ammunition.

The shots were fired toward a piece of corrugated cardboard located 50 m from the muzzle. This cardboard was later scanned and digitally combined with circles indicating the biathlon targets, printed on a plastic transparency.

The transparency with the biathlon target indications was centered over the series before scanning because the rifle was not zeroed for every type of ammunition. This visualization gives a simple illustration of the performance of the different ammunition in relation to the biathlon target size.

Performance at 22°C

The performance at this temperature was evaluated to show the performance of the different cartridges during summer conditions. These tests were performed at an outdoor shooting range, meaning that even if the wind during the test was measured to be less than 1 m/s there could possibly be wind gusts, etc., that could influence the result. All conditions could, however, be considered fairly constant during the full test.

The results from 22°C for the two test rifles were shown in Figure 5 and 6. All shots presented in these figures were also monitored through an external high-magnification scope to ensure that no type of strange behavior that could indicate problems with the rig were present. All hits were, however, shown to be fully stochastically distributed (within the target zone), which was seen as proof that the results were a good statistical basis for the evaluation of the ammunition types.

CCI std is considered by many as a good budget alternative to competition ammunition. This ammunition is a traditional lead-based cartridge which has a decent performance, as seen in Figures 5(a) and 6(a). Actually when comparing the performance of the CCI std to the significantly more expensive competition ammunition in Figures 5(b) and 6(b) there is not a huge difference in performance except for two outliers with CCI std in one of the test rifles, see Figure 6(a). CCI std could therefore be seen as a baseline for the standard of performance you can get from an inexpensive training ammunition of a traditional lead type. It is clear from the results that it is possible to manufacture high quality ammunition for a fraction of the cost of competition ammunition, that could be considered good enough for practice and competition unless you are competing on a professional level.

Figure 5(b) show a series from competition ammunition (Lapua Polar Biathlon) specially designed for use in cold temperature biathlon competitions. This ammunition is expected to give a minimal spread and to produce even results with as few outliers as possible.

While the performance of the two tested types of lead-based ammunition (budget and competition ammunition) both show a decent performance, the performance of the two tested lead-free ammunition types is much worse, as shown in Figures 5(c) and (d), 6(c) and (d). Clearly, these lead-free ammunition types have a much larger spread than the different lead-based cartridges. The best-performing lead-free cartridge has a spread of 61 mm c-c, that is, around 67 mm (61 + 5.6 mm) on the outer edge of the test series, which is around 50% larger than the size of the smaller target in the biathlon (45 mm) and would therefore not work at all in a biathlon competition. This performance could also be compared to the lead-based competition ammunition, which performed a 25-shot series with around 25 mm maximum spread (c-c) under the same conditions. Table 4 shows the maximum spread for all 25-shots series.

Performance at −12°C

The performance at this temperature is evaluated for each cartridge with a five-shots series as a complement to the longer summer series, to show the performance of the different cartridges during winter conditions. These test series were performed at an outdoor shooting range, meaning that even if the wind during the test was measured to be less than 1 m/s there could possibly be wind gusts, etc., that could influence the results. All conditions could, however, be considered fairly constant during the full test.

The results from −12°C for the two different test rifles are shown in Figures 7 and 8. Even if these shorter test series give a smaller statistical base for evaluating the performance than the 25-shots test series performed at 22°C, it is still shown without any doubt that the trends that were obvious at 22°C are also visible at lower temperatures and winter conditions, that is, that the performance is much worse for the tested lead-free cartridges than for the lead-based cartridges.

Bullet velocities

The measured bullet velocities are shown in Table 3. When analyzing these velocities, it should be noted that the displayed values of the series at + 22°C have a larger statistical base compared to the series performed at −12°C, meaning that the + 22°C series are expected to have a larger spread in extreme velocities (EXT).

From Table 3 it is clear that the lead-based ammunition has a very even performance and that the variation in velocity is much larger for the relatively fast lead-free bullets. The two lead-free types are also shown to have a much lower velocity in comparison to their specification, see Table 2, which might be because of the barrel length on the rifles used in the tests. The barrel length is not of great importance for the performance of normal 22lr ammunition but could potentially be of importance for these high-speed cartridges which might need a longer barrel for the powder to burn sufficiently and accelerate the bullet to the higher speed. Something that is also evident from Table 3 is that the lighter and faster lead-free bullets from Norma Eco Speed 22 lose more velocity before the target at 50 m than the heavier and slower lead-based bullets. This outcome makes sense because of higher air resistance due to the higher muzzle velocity in combination with a lighter bullet.

The velocity of CCI Copper 22 was not possible to measure with good precision. The reason for the difficulties to measure the speed for this ammunition is unclear, but it might have to do with the special compounds of the bullet that could make it more difficult to measure due to a lower density, or because the Labradar equipment used in this work (in Sweden) is less powerful than the original US-version, because of EU-regulations, and has a 30% reduced tracking capability.[13]

Spread at 50 m shooting distance

Table 4 shows the maximum spread (c-c) between the 25 shots in each test series performed at an air temperature of 22°C. From this table it is obvious that the lead-based cartridges perform much better than the lead-free ones. The more expensive lead-based competition ammunition (Lapua Polar Biathlon) shows more consistent behavior than the cheaper ammunition (CCI std). CCI std has, however, a comparable performance for most shots but also produced a few outliers, as seen in Figure 6(a) where two shots are visible in the upper left corner of the group. Without these two outliers the spread is 26 mm, which is similar to Lapua Polar

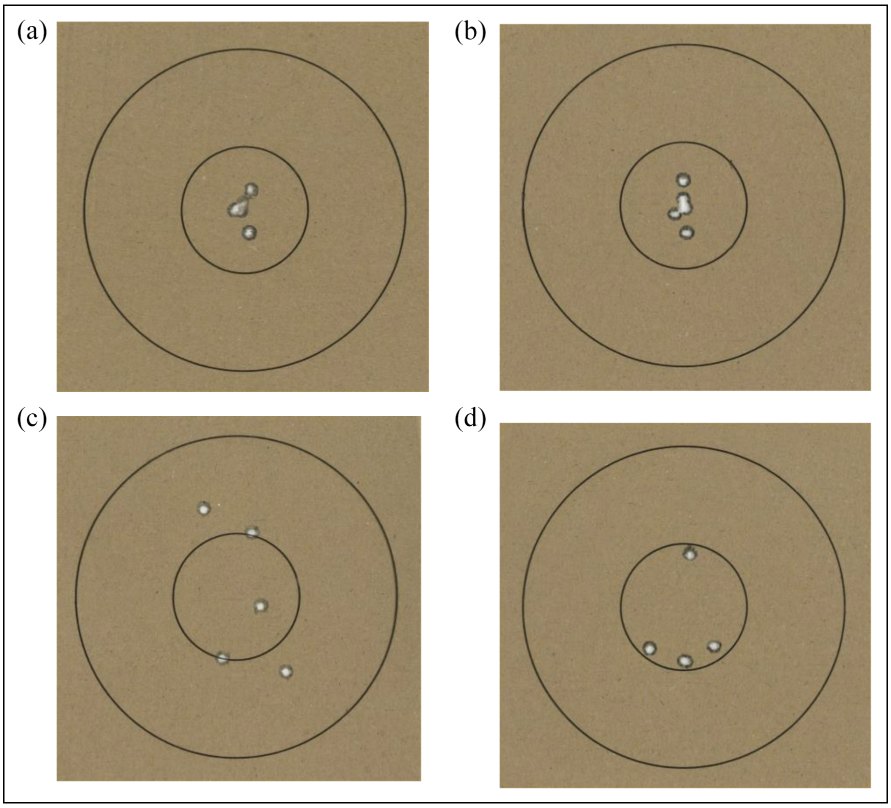

Figure 7. Typical results from test series at −12°C. The results are shown in relation to the two target sizes in the biathlon, 45 and 115 mm. Test rifle: Ruger American Rimfire Target: (a) CCI std, (b) Lapua Polar biathlon, (c) CCI Copper 22, and (d) Norma ECO Speed 22.

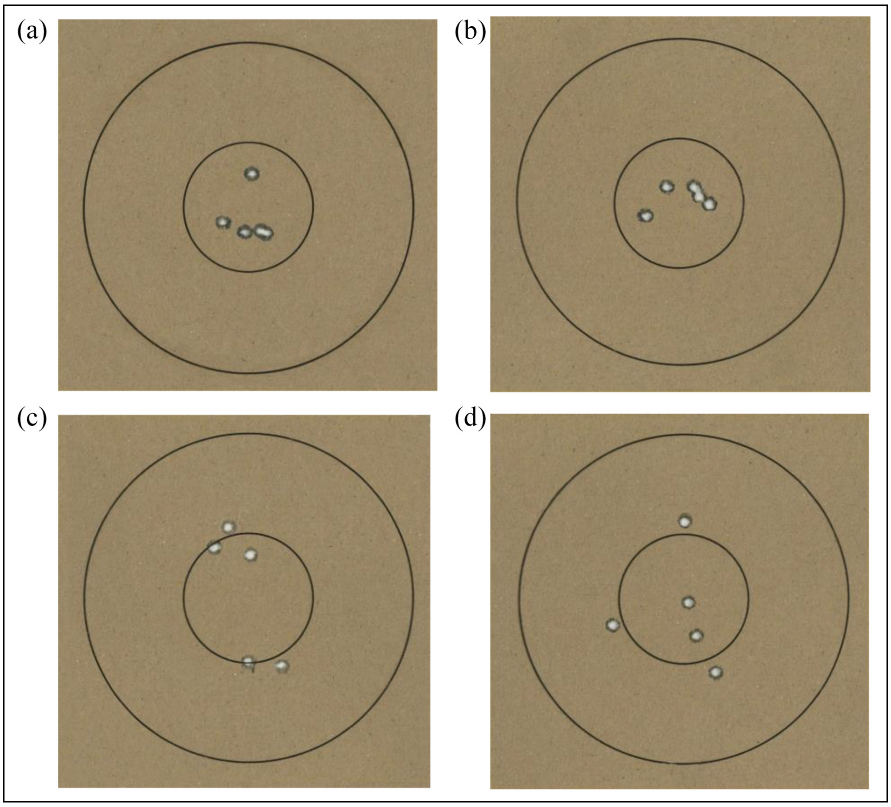

Figure 8. Typical results from test series at −12°C. The results are shown in relation to the two target sizes in the biathlon, 45 and 115 mm. Test rifle: BRNO CZ 457: (a) CCI std, (b) Lapua Polar biathlon, (c) CCI Copper 22, and (d) Norma ECO Speed 22.

Table 4. Spread (C-C) at 50 m for the 25-shot series at a temperature of 22°C, shown in Figures 5 and 6.

Cartridge	Ruger American Rimfire Target (mm)	Brno CZ 457 (mm)
CCI std	27	44
Lapua Polar biathlon	25	26
CCI Copper 22	68	61
Norma Eco Speed 22	67	74

Biathlon, but these outliers are detrimental for top-level precision shooting. Even with these outliers the performance of the CCI std is much better than the two tested lead-free cartridges where the spread is much larger than the smaller target in the biathlon.

Discussion

This investigation was made to evaluate the performance of lead-free ammunition in caliber 22lr. The results have been evaluated at a shooting distance of 50 m toward the target size in a biathlon competition, that is, a target diameter of 45 mm for series when the shooting is performed while lying down and 115 mm for standing up. A shooting distance of 50 m is also common in other rifle sport shooting disciplines where 22lr is used. The results are illustrated by a 25-shot series in the main investigation at summer temperatures and a five-shot series for complementary results during winter temperatures. The shots are fired from a rifle attached to a specially developed shooting test rig where the shooter is eliminated from the actual aiming and firing to give a good repetitiveness and an optimal comparison between the different types of ammunition. Due to the good receptiveness of the results, there is no doubt that valid conclusions could be made from the resulting test series.

Today there are only a handful of lead-free alternatives for the 22lr cartridge available in the market, but a huge number of lead-based cartridges. To limit the investigation, two options of lead-based ammunition were evaluated together with the two existing lead-free alternatives that were available. These two lead-free cartridges were also manufactured with completely different bullet technologies.

The two lead-based cartridges were chosen to cover the full price range of lead-based 22lr ammunition, with one being one of the cheapest possible training ammunition available and the other an expensive competition ammunition specially developed for biathlon competitions.

The results of this study clearly show that the performance of the tested lead-free types of 22lr ammunition is not as good as that of the lead-based ammunition. Both the tested lead ammunition cartridges were shown to give a consistent result with little spread and that shows how well-developed the lead-based ammunition is, and how well-adapted the rifles using 22lr are to this ammunition. The main difference between those two cartridges was shown in the 25 shots series where the cheaper ammunition produced a few outliers in one of the test series while the competition ammunition did not. Such outliers are obviously not acceptable for top level athletes, but for many sports shooters the cheapest option would still be sufficient for both training and competition.

The tested lead-free ammunition, on the other hand, showed poor performance, meaning that lead-free ammunition is not a viable option for sport shooting. The results from the tests show that the spread at 50 m for the best performing lead-free cartridge is about 50% larger than the smaller target size in the biathlon, while the worst of the tested lead-free ammunition produces a group that is almost equivalent to the larger target size in the biathlon. This large spread means that if lead-free ammunition was to be used in a biathlon competition, the shooting aspect of the competition would be totally randomized and have almost nothing to do with the skill of the shooter. For other types of sport shooting, where precision is even more important, this poor performance is even more detrimental. Therefore, it can be clearly concluded that the existing lead-free ammunition is not accurate enough to be used in any kind of serious shooting activity.

The cost of these lead-free alternatives is also much higher than the cost of the lead-based ammunition available on the market, where the cheaper lead-based alternatives could also show a good performance. The cost of lead-free ammunition could be reduced in the future if lead-free ammunition production is increased, but the lack of performance is a more difficult issue to solve. The poor performance of the existing lead-free 22lr cartridges could probably be seen as proof that it is difficult to design a lead-free 22lr alternative, because of the ballistics, where a relatively short and slow bullet is difficult to stabilize if the bullet becomes too light, that is, when the lead is replaced with some material with a lower density.

The results of this work also show that the velocity of the lead-free ammunition is much lower than the indicated speed from the manufacturer. The velocity also showed a much larger decrease in velocity for both tested lead-free alternatives at lower air temperatures, that is, winter conditions, when compared to the lead-based cartridges.

The velocity of the lead-free bullets also decreased up to about 100 m/s in velocity, compared to the muzzle velocity, after traveling only 50 m in the air. That could be compared to the lead-based ammunition which only decreased around 30 m/s or less for the same distance. This decrease in velocity means that the lead-free ammunition has much less energy left at the target at 50 m compared to the lead-based ammunition, which is especially detrimental in competitions with falling targets such as in the biathlon.

Conclusions

All results in this investigation highlight the difficulties of replacing lead with other materials in caliber 22lr ammunition. This caliber is the most widely used caliber in the world and is common for sport shooting in many disciplines. However, the performance of the tested lead-free cartridges is shown to be too poor to be used in sport shooting. The results show that the proposed EU lead ban for ammunition would be responsible for causing major damage to sport shooting in Europe, at least until new types of ammunition with acceptable performance and cost could be presented.

Furthermore, the investigations made previously, regarding lead pollution from shooting ranges, show that the risk of lead pollution from bullet traps at a shooting range is so low that there is no motivation to introduce a lead ban for shooting ranges. Therefore, all shooting activities at shooting ranges, covering both sport shooting and practice shooting, should be excluded from a possible future lead ban.

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References

1. TNS Political and Social Network. Firearms in the European Union. *Flash Eurobarometer*, 383, 2013.
2. Eurostat press office. European demography. *Eurostat Newsrelease*, 173, 2013.
3. Pain DJ, Mateo R and Green RE. Effects of lead from ammunition on birds and other wildlife: a review and update. *Ambio* 2019; 48(9): 935–953.
4. Qvarfort U, Leffler P and Sjöström J. Vitbok - Om bly i kulfång. *FOI CBRN-skydd och säkerhet*, 2008.
5. Lewis J, Sjöström J, Skyllberg U, et al. Distribution, chemical speciation, and mobility of lead and antimony originating from small arms ammunition in a coarse-grained unsaturated surface sand. *J Environ Qual* 2010; 39(3): 863–870.
6. Edlund C, Genberg H, Liljedahl B, et al. Miljöriskbedömning av kablar i mark vid militära anläggningar. *FOI -Totalförsvarets forskningsinstitut*, 2001. FOI-R–0220–SE.
7. Hampton JO, DeNicola AJ and Forsyth DM. Assessment of lead-free .22 lr bullets for shooting European rabbits. *Wildl Soc Bull* 2020; 44(4): 760–765.
8. Trinogga AL, Courtiol A and Krone O. Fragmentation of lead-free and lead-based hunting rifle bullets under real life hunting conditions in Germany. *Ambio* 2019; 48(9): 1056–1064.
9. Thomas VG and Kanstrup N. Promoting enforcement of non-lead hunting ammunition regulations and compliance in Europe and North America. *Ambio* 2023; 52(8): 1350–1358.
10. Thomas VG, Kanstrup N and Fox AD. The transition to non- lead sporting ammunition and fishing weights: review of progress and barriers to implementation. *Ambio* 2019; 48(9): 925–934.
11. Kanstrup N and Thomas VG. Transitioning to lead-free ammunition use in hunting: socio-economic and regulatory considerations for the European Union and other jurisdictions. *Environ Sci Eur* 2020; 32(1): 91.
12. McTee M and Ramsey P. Is lead-free .22 long rifle ammunition worth a shot? *Wildl Soc Bull* 2022; 46: 166288.
13. https://mylabradar.com/ (accessed 25 May 2023).