Arrow Lethality

Part IV: The Physics of Arrow Penetration

By Dr. Ed Ashby

Kinetic energy, momentum, mechanical advantage and coefficient of resistance are a part of the basic terminology of physics. All are used, and often misused, in attempts to predict terminal performance of various bow, arrow and broadhead combinations. Much of the misuse originates from a lack of understanding of what, by definition, these terms mean and what it is they measure.

In the terms of physics, all broadheads are classed as "simple machines." As such, all broadheads are no more than a series of inclined planes. The mechanical advantage (M.A.) of a "simple machine" is the ratio of the resistance to the effort. The mechanical advantage of an inclined plane is equal to the length of the plane divided by the height of the plane.

A single blade broadhead, with a straight taper, 1" wide by 3" long can be viewed as two inclined planes, each of which has a mechanical advantage of 6.0 (3" divided by 1/2"). The mechanical advantage of the two planes combined would be 3.0 because the height would be doubled while the length remains the same. What this means is that with an exerted force (effort) of 1 pound, a weight of 3 pounds can be lifted from the tip of the broadhead to the back edge of the broadhead. The higher the M.A. the more work a broadhead can do with the force available.

To determine the mechanical advantage of any broadhead with a straight taper to the cutting edge, divide the horizontal length of the cutting blade by 1/2 the width of the broadhead (or, more precisely, the distance from the central axis of the arrow to the highest point on the plane) multiplied by the number of blades. In an equation this would be expressed as:

$$\text{M.A.} = \frac{\text{Length of cutting blade}}{(\text{1/2 width of head}) \times (\text{number of blades})}$$

Example #1

As stated above, a single blade broadhead 3" long by 1" wide has a mechanical advantage of 3.0. If that same head has three blades, the M.A. would be 2.0, ie: (3" length/.5" lift distance X 3 blades). If it had four blades, the M.A. would be 1.5, or one half that of the single blade.

Example #2

In a broadhead with a cutting edge length that is 2.25" long and with each blade .75" high (a common dimension) the M.A.s work out as follows:

Single blade head => M.A. = 1.5
Three blade head => M.A. = 1.0
Four blade head => M.A. = 0.75

Five blade head => M.A. = 0.6
Six blade head => M.A. = 0.5

(Note: this is 1/2 the M.A of the 1" X 3" single blade broadhead.)

In example #2, a single blade head would be able to do 50% more work than a three blade broadhead with the same applied force. It does 100% more than the four blade, 150% more than the five blade and 200% more than the six blade broadhead.

The mechanical advantage equation dictates that the greater the length of a broadhead relative to the width, and the fewer the number of blades, the more efficiently it will be able to utilize the force applied to it.

Kinetic vs Momentum

As a base point for a discussion of momentum and kinetic energy, one must understand that the laws of physics dictate that energy can never be manufactured or destroyed but only transformed or directed in its flow. The equations for these two measurements are:

Kinetic Energy =

$$\frac{\text{Weight X Velocity Squared}}{\text{2 X Acceleration of Gravity}}$$

Momentum =

$$\frac{\text{Weight X Velocity}}{\text{Acceleration of Gravity}}$$

The kinetic energy (K.E.) of a moving body increases as the *square* of the velocity and directly as the mass whereas the momentum increases directly as *both* the velocity and/or mass increases .

With the advent of compound bows and overdraw setups, with their higher velocity capability, it has become common to see kinetic energy figures cited as a supposed measure of the penetration capability of a particular bow-arrow-broadhead combination. This use of kinetic energy reflects a misunderstanding of these basic principles of physics.

By *definition*, kinetic energy is the capacity to do work. It is the TOTAL ENERGY of a body in motion. **K.E. is scalar, or nondirectional, in nature.** As applied to an arrow in motion, K.E. includes such things as: radial energy due to arrow flexion; rotational energy due to arrow spin; sonic energy due to vibration; heat energy due to friction; and potential energy (all other remaining energy). Simple use of K.E. alone as a predictor of penetration capability also fails to take into consideration the mechanical advantage of the broadhead and the coefficient of resistance. The kinetic energy of an arrow, *by definition*, **is not** a direct indicator of the penetration capability of the bow-arrow-broadhead combination.

Momentum is the measure used in physics to quantify the "impulse"; the force exerted over a period of time **IN ONE SPECIFIC DIRECTION.** **Momentum is a unidirectional force vector.** Another of those basic laws of physics states that "in cases of collision, whether the bodies are elastic or inelastic, the momentum before collision is equal to the momentum after impact." This means that momentum is the measure of how much energy, due solely to the weight and velocity of an arrow, must be transferred to whatever it impacts before the arrow comes to rest. (Again, momentum alone will not fully predict the penetration capability of an arrow, and the mechanical advantage of the broadhead and the coefficient of resistance must also be considered.)

Assuming there is no bending of broadhead or arrow shaft, how far into the target an arrow will go before all available energy is lost (the amount of penetration) depends on four MAIN factors: the resistance of the object impacted (target), the momentum of the arrow, the efficiency with which the arrow (broadhead) utilizes the force available to it and the resistance of the arrow (often expressed as the frictional or drag coefficient). The resistance of the target we have little control over. Arrow and broadhead selection we do have control over.

Use of a broadhead with a high MA results in maximum utilization of whatever momentum is available. High MA broadheads also offer lower tissue resistance.

Heavy arrow mass helps maintain high momentum throughout the arrow's full flight. Velocity diminishes very rapidly but arrow mass remains constant throughout the full flight of the arrow (which is why bow draw-weight is less important than arrow mass).

Shafts with diameters equal to, or smaller than, the ferrule reduces the drag factor of the shaft on tissues as the arrow penetrates. Broadheads with smooth contours, having no abrupt angles or juncture points, also reduces the drag factor. Combined, these factors help maximize the penetration capability of hunting arrows, regardless of what target resistance is encountered.

The following charts give the calculated momentum of one of the better performing combination tested in the Natal Study (adequate for all shots on game up through zebra size when used with a ***good*** broadhead of at least 3.0 MA) and compares it with the momentum of common rifle and handgun loads. They also demonstrate the measured effect on the momentum of increased arrow mass. While arrows certainly penetrate tissue with much less effort than a bullet, an arrow used on big game must still maximize the use of its very limited energy. There is no excess to spare!

Graph XIV is intended to allow the reader to calculate various arrow weight and velocity combinations that will give a momentum (.57 Pound-Seconds) equal to that 'adequate' basic big-game arrow used in the example (assuming the same 'good' broadhead is used).

It will be noted that, with current equipment, it is impossible to generate this amount of momentum with light weight arrows. Even at an arrow mass of 520 grains, the velocity needs to be near 250 feet per second, yet a heavy arrow of 740 grains need only be traveling a little over 160 feet per second to reach this level of momentum (a velocity easily within the capability of most conventional and compound bows of only modest draw weight)

In Part V: Predicting Arrow Penetration on Real Animals we will look at the potential practical application of the information presented in the previous articles, and a first field test of its capability.

Momentum and Mass

Momentum=

Mass in lbs. X Velocity in ft./sec =>

$$\frac{\text{Pound Seconds}}{\text{32 ft./sec./sec}}$$

2219 shaft w/190 gr. Grizzly (710 gr.) at 180.5 Ft./Sec. => .57 Pound-Seconds

22 Hornet 45 Grain at 2690 Ft./Sec. =>

.54 Pound-Seconds

.38 Special 158 Grain at 755 Ft./Sec. => .53 Pound-Seconds

.357 Magnum 158 Grain at 1250 Ft./Sec. => .88 Pound-Seconds

TO ACHIEVE .57 POUND-SECONDS OF MOMENTUM: (The average momentum of the "Adequate" performing arrow/broadhead combinations in Natal Study, <u>all of which had broadheads of 3.0 mechanical advantage and shafts equal to, or smaller than, the broadhead ferrule in diameter</u>):

A 900 Grain Arrow must reach a velocity of 142 Ft./Sec.

A 740 Grain Arrow must reach a velocity of 161 Ft./Sec.

A 550 Grain Arrow must reach a velocity of 234 Ft./Sec.

A 450 Grain Arrow must reach a velocity of 285 Ft./Sec.

A 350 Grain Arrow must reach a velocity of 367 Ft./Sec.

Effect of Increased Arrow Mass:

With 94# longbow:

A. Arrow of 650 Grains has 184.5 FPS velocity and Momentum = .54 Pound-Seconds.

B. When arrow mass is increased to 785 Grains, velocity is 175 FPS velocity and Momentum = .61 Pound-Seconds.

C. When arrow mass is increased to 1286 Grains velocity is 154 FPS and Momentum = .88 Pound-Seconds.

In these examples an increase in arrow mass of 21% results in a velocity decrease of only 5.1% but increases momentum by 12.9% (Arrow 'A' compared to Arrow 'B'). A mass increase of 98% results in a velocity decrease of only 16.6% and a momentum increase of 63% (Arrow 'A' compared to Arrow 'C').

Of historical note, Art Young and Saxton Pope used 75# selfwood longbows and 3/8" birch shafts with broadheads 1" wide by 3" long (arrow mass of *approximately* 800 grains at *approximately* 155 FPS for a momentum of .55). With these they were able to completely penetrate (with arrow exit) Alaska brown bears, and Young successfully took many of the larger Africa species, including several lion and Cape buffalo, with the same equipment. He was unable to achieve adequate penetration on black rhino with this combination.

Postulates Based on Arrow Penetration Test of Game Animals

I have formulated the following postulates which were originally developed from data secured during the Natal Study. All subsequent testing I have conducted to date have supported these original postulates.

1. Many broadheads are too fragile, bending or breaking on impact, thus limiting penetration.

2. Broadheads <u>*must*</u> remain undamaged. A broadhead that becomes bent or broken on impact will severely limit penetration.

3. There is a <u>*direct correlation*</u> between the depth of arrow penetration and per-

centage of killing hits. The deeper an arrow penetrates, the more likely it is to kill.

4. There is *no correlation* between broadhead size, increased number of blades or 'cut area' and the percentage of killing hits.

5. Given a well placed hit with a sharp broadhead, broadhead failure and inadequate penetration are the only two things which cause failure to kill.

6. Rigid single blade broadheads are the least prone to damage on impact.

7. The most lethal shot angle is with the animal quartering away from the archer.

8. The least lethal shot angle is with the animal quartering towards the archer and the shot hitting in the neck-shoulder junction area.

9. All multiblade broadheads offer insufficient penetration when heavy bone is encountered.

10. Single blade broadheads penetrate significantly better than multiblade broadheads in both soft and hard animal tissue.

11. Four and five blade heads penetrate bone better than three blade heads.

12. When a rib is hit on entrance, a single blade broadhead is almost twice as likely to be lethal as 4, 5, and 6 blade heads and three times as likely to be lethal as three blade heads.

13. When heavy bone is encountered, a total arrow mass of at least 650 grains, as well as a tough single blade broadhead, is required to achieve adequate penetration.

14. A single blade broadhead is more than twice as likely to produce an exit wound as a multiblade broadhead.

15. The degree of blood trail is dependent on the location of the hit and the presence/absence of an exit wound, not the number of blades on the broadhead.

16. When all shots are considered, the degree of wound inflicted (depth of wound channel times the blade cut) by single blade broadheads is equal to or greater than that inflicted by multiblade broadheads.

17. No multiblade broadhead can reasonably be expected to penetrate even a deer size animal when the hit is from the forward quartering angle and in the area of the neck-shoulder junction.

18. The most important factor in achieving adequate penetration is a well constructed single blade broadhead.

19. The second most important factor in achieving adequate penetration is adequate arrow mass (a minimum mass of 650 grains is recommended for 'standard' big game animals and 900 grains for 'super size' game).

20. The third most important factor in achieving adequate penetration is having a shaft diameter no larger than, and preferably smaller than, the broadhead's ferrule in diameter.

21. Game animals have reflexes faster than even the very fastest of arrows. No archer can guarantee where his arrow will strike an animal.