Impact of reproductive technologies on improved genetics in beef cattle

JE Kinder[1], JM Osborne[1], ME Davis[1], ML Day[1]

[1]The Ohio State University, Department of Animal Sciences, Columbus, Ohio 43210, USA

Introduction

Domestication of food producing animals has led to the desire by humans to control reproduction so as to enhance production of the products (e.g., meat) from these animals. Domestication of cattle is estimated to have started about 10,000 years ago (Bradley et al., 1998). Controlled reproduction by regulating mating patterns, through use of natural breeding, has long been practiced by those who manage food producing animals. The utilization of reproductive technologies has, therefore, evolved in food animal production so as to allow producers further control over reproduction. These technologies allow for genetic improvement through increasing the selection differential with use of the most elite genetically proven individuals by mating the "best to the best", reducing the generation interval by decreasing the age at which breeding commences, and increasing the frequency at which these elite individuals can produce offspring (by harvesting eggs, spermatozoa, or embryos).

In this review, we will assess the impact that implementation of these reproductive technologies has on genetic improvement in the beef industry. Reproductive technologies are those for controlling and inducing initiation of oestrous cycles during sexual development or during the postpartum period (e.g. synchronization of oestrus), artificial insemination, sexed semen, multiple ovulation and embryo transfer (MOET), and cloning, along with accompanying transgenic approaches are assessed. Genetic variables such as genetic gain per unit of time, progeny superiority as a result of the increased selection differential, decreased generation intervals, and extent of inbreeding resulting from use of reproductive technologies are assessed in this review because these are indicators of the impact that use of these technologies has on improving genetics in beef cattle.

Reproductive Technologies

Introduction

Only a brief overview of the reproductive technologies will be provided in the present review. There has recently been an excellent review of these reproductive technologies conducted by Basrur and King (2005). The authors of the present review suggest that this previous review be used for a more intensive evaluation of these technologies and impacts on genetic improvement.

Control and Induction of Oestrous Cycles

The goal of use of this technology is to produce more offspring from genetically superior animals. There has been great emphasis in the last 50 years on the development of methods to control the time of behavioural oestrus and ovulation in cattle. Great progress has been made in the technologies to control the timing of these behavioural and physiological variables. Induction of oestrus and ovulation in prepubertal heifers, or postpartum anoestrus females that are approaching the period when they would naturally initiate oestrous cycling, can be accomplished by the use of the steroid hormones, progestins and oestrogens. Control of the time of ovulation and behavioural oestrus in cattle that have previously initiated the onset of oestrous cycling can be accomplished by the use of progestins and oestrogens in a similar regimen as that used to induce onset of oestrous cycling. Prostaglandin F2α can be used to synchronously induce regression of the corpus luteum in a group of cattle, which results in onset of oestrus at a similar time among females (i.e., synchronisation of oestrus). These technologies have typically been used in combination with artificial insemination to facilitate AI rather than as a technology that is used with genetic improvement as the primary focus when adopting the technology.

In 1991, Gareth Evans indicated in a scientific manuscript reviewing the reproductive technologies – "Fixed-time AI has been used in heifers with some degree of success, but in lactating cows better results are usually obtained when AI occurs at a time related to onset of oestrus than at a fixed time related to synchronization of oestrus" (Evans, 1991). There has been considerable enhancement of the technologies for oestrous and ovulation control since that time, and beef producers in the US systems are increasingly turning to programs in which timed AI is used exclusively, or programs that involve a combination of a short period oestrus detection and AI (2 to 3 days) with timed AI in all animals not detected in oestrus as the methods of choice. The increase in submission rate associated with these programs as compared with traditional oestrous detection programs often results in increased pregnancy rates during the synchronization period. Furthermore, the opportunity to manage cattle herds as a group, rather than as individuals based upon the time that they exhibit oestrus has allowed producers with limited labor to schedule AI programs, rather than have these dictated by the time of oestrus. The availability of these approaches to control and induce oestrous cycles in beef cattle has been integral in enhancing the use of AI in the USA.

Artificial Insemination

This technology has been used in cattle for over 65 years (Foote, 2002; Betteridge, 2003). We are fortunate in the cattle industry to have a long standing method to effectively and efficiently cryopreserve spermatozoa in a manner that these cells remain viable and retain the capacity for fertilisation subsequent to thawing. Cryopreservation of spermatozoa is a technology that is often taken for granted in the cattle industry, but that has not been accomplished in most other food producing species. For example, domestic turkeys used for meat production in the USA no longer have the capacity to naturally mate. The sole route of insemination of female turkeys is via artificial means, but with use of fresh semen, because of the inability of the turkey spermatozoa to withstand freezing and thawing procedures and still remain viable. The reproductive technology of artificial insemination should, therefore, not be taken for granted as a valuable technique to enhance genetic improvement in beef cattle.

Sexing Semen

The capacity to sex semen is a reproductive technology that has existed in beef cattle for several years. This technology is based on what is referred to as the "Beltsville Sperm Sorting System" (Harlizius et al., 1995; Maxwell et al., 2004). This approach uses the technique of flow cytometry to separate spermatozoa with X bearing chromosomes from those with Y bearing chromosomes. Refinements of the system allow for the sorting of 15 million cells per hour (Seidel et al., 1999; Seidel, 2003). Nevertheless, the number of spermatozoa available for AI is less after sorting, particularly if only one sex of the gametes is preferred to be used for AI. There are lesser numbers of spermatozoa used because of technology deficiencies in sorting the large number of spermatozoa typically used for each AI with "sexed semen" as compared with normal AI practices. There is also decreased viability of spermatozoa as compared with typical systems of spermatozoa harvesting and cryopreservation. Special attention is, therefore, given when using "sexed semen" to inseminate closer to the time of ovulation and deeper into the uterus so as to compensate for the lesser number of viable sperm cells used per AI dose. There are, nevertheless, decreased pregnancy rates when "sexed semen" is used compared with when typical "non sorted semen" is used for AI (Sartori et al., 2004).

The ability to advance this technology to the extent that it can be used commercially in the cattle industry has only occurred in the last decade. The initial commercial venture in this area for cattle has recently occurred in the USA. Select Sires, Plain City, Ohio is marketing sexed semen at the present time. Genex Cooperative Inc. and Cooperative Resources International (CRI), another supplier of cattle semen for AI, will be marketing "sexed semen" via the Decisive™ trade label within the next 6 months. This technology was perfected by Monsanto, the leading company in the USA in marketing biotechnologies relevant to agriculture, and licensed by them to Genex. Obviously, this technology allows for controlling the gender of calves to a greater extent than with the typical 50:50 ratio that occurs with natural mating or artificial insemination. The use of "Sexed semen" has been reported to result in 87.8% heifers from "X sorted" spermatozoa and 92.1% bulls after AI with "Y sorted" spermatozoa (Seidel, 2003; Tubman et al., 2004). The sex sorting accuracy is, therefore, about 90%.

Multiple Ovulation and Embryo Transfer

The ability to increase the number of ovulations over that which typically occurs in cattle through use of hormonal treatments is a technique that has existed for over 50 years, but has only been developed commercially in the last few decades. It has emerged as an effective and efficient way of transmitting the genetics of superior female cattle after development of non-surgical methods for collection and transfer of embryos. The techniques for inducing multiple ovulations (super ovulation), developing multiple embryos (either in vivo or in vitro), and transferring these embryos to females that are deemed of less genetic value (recipient females) have evolved and are being used in specific segments of the beef industry, particularly the purebred industry in the USA.

Cloning and Transgenesis

Division of developing embryos to produce identical offspring is a reproductive technology that has existed for several decades and there have been commercial ventures to utilise this technology in the beef industry. Removing somatic (non germ) cells from an adult and producing a clone is the most recent reproductive technology developed for use in cattle. This technology involves inserting the genetic material from a somatic cell into an enucleated cattle egg. Cloning, therefore, allows for production of a genetic copy of an already genetically proven animal.

Transgenesis involves introducing a specific gene or genes into the genome, ensuring stable incorporation in the genome, and thus the ability to transmit this gene in future generations. This allows for incorporation of genes in ways that were only accomplished through crossbreeding previous to development of this technology. Transgenesis thus offers a more rapid method for introducing new and desirable genes into a specific genome.

There are significant problems with these technologies because many of the developing embryos and fetuses do not survive in utero. Furthermore, many of those that do survive the typical gestation period are not delivered at term, are unusually large at term (First et al., 1999; Betteridge, 2003), or die at or shortly after birth (First et al., 1999). Another problem with these technologies is the acceptance by society of the food produced by animals that are derived using cloning and transgenic technologies.

Impact of Reproductive Technologies on Genetic Improvement in Beef Cattle

Introduction

Reproductive processes can be compromised at many different stages in both male and female cattle. Reproduction can, therefore, be compromised at gametogenesis (egg and sperm production and development), joining of the two gametes (fertilization), embryonic or fetal development, and subsequent to birth of the calf. When the use of reproductive technologies compromises reproduction at any of these stages, the rate of genetic progress is decreased relative to what would ideally occur.

Control and Induction of Oestrous Cycles

There has been significant implementation of oestrous cycle and ovulation time control technologies in purebred beef operations for breeding of 1-year-old heifers in the USA. The reason for this is the predictability of birth weight, which is a highly heritable trait, by using sires, primarily from AI Studs, that have large numbers of records, and thus more precise predictability for calving ease.

Other than enhanced use of AI that results from use of the reproductive technologies for oestrous cycle control, there is little evidence in the scientific literature that indicates an enhanced rate of genetic improvement through application of these technologies. Although the use of AI in beef operations in the USA has been slower to develop than AI with many other food producing species, the extent to which it is used is unquestionably enhanced because of development of oestrous cycle control technologies. Thus, these technologies impact genetic improvement of beef cattle in the USA through enhanced use of AI, but the magnitude of the direct impact on genetic improvement has not been estimated either for oestrous cycle control or induction of onset of oestrous cycles in heifers (to induce onset of puberty) or cows (to induce onset of estrous cycles during the postpartum period). This technology is, therefore, used to a greater extent, at present, as a management tool to make the use of AI more feasible than as a technology for enhancing genetic improvement.

Artificial Insemination

Of all the reproductive technologies, AI was the first to be developed and remains the most important for genetic improvement in beef cattle. The genetic selection that has been used by beef AI studs through mating of bulls to cows based on superior genetic values and subsequently randomly mating the sons that result from this mating practice through AI to determine which bulls to use has resulted in significant genetic improvement (genetic gain per unit of time, progeny superiority – both as a result of the increased genetic selection differential). In dairy cattle, the use of natural breeding under optimal scenarios is estimated to provide genetic gains of 0.5 to 0.6% each year. Optimum use of AI is estimated to increase rate of genetic improvement to 2.0 to 2.5% in dairy cattle but these figures are not known for beef cattle (Van Vleck, 1981). A factor that decreases the rate of adoption of AI in the USA beef industry is the lack of an obvious single trait on which to focus genetic selection such as occurs in the dairy (i.e., milk production) and turkey (i.e., muscle accretion/unit of time) industries. Therefore, selection for growth or some other highly heritable trait in the beef industry has not been focused on in a manner to maximize genetic gain per unit time as has occurred with single trait selection in some other food producing animals. This less intensive selection in the beef industry has also avoided some of the phenotypic defects that result from undesirable genetic correlations that have led to decreased reproduction in dairy cattle and decreased structural soundness in turkeys as a result of the focus on single trait selection with these food producing animals in the USA.

The enhanced genetic gains that occur with use of AI also result from a somewhat shorter generation interval, because progeny of sires can be obtained and assessed for genetically desirable traits in a shorter period of time than with natural service. AI is the reproductive technology, therefore, that has the greatest impact on genetic improvement of beef cattle. Inbreeding depression of performance with use of AI has not been a factor in beef cattle because of the large population of cows and the many bulls that have been used. This technology has, therefore, been used for many years without detrimental impacts of enhanced inbreeding, which was a concern when this technology was originally developed.

This technology would have a greater impact if AI were used more widely in beef operations. It is estimated that less than 10% of beef females are bred by use of AI in the USA, with little increase during the past decade (National Association of Animal Breeders, 2003). This technology has, nevertheless, had a great impact on genetic improvement in the USA because of the extent of adoption in purebred beef herds. At present, adoption of AI in the Hereford, Charolais, Simmental, and Angus purebred herds in the USA is, approximately 12, 15, 40, and 47%, respectively. In the case of Angus purebred cattle, there is a 1% increase annually in the percentage of the breed in which calves are produced through use of AI (personal information, R. Wallace – Select Sires AI Stud, Plain City, Ohio USA).

The ability to use and transport the semen of bulls worldwide allows for spread of the genetics of elite and genetically proven bulls to a greater extent in cattle than in any other species. An example of this is that 16 of the top 25 Angus bulls in the Australia Angus Sire Summary are bulls that reside in the USA and many of the other 9 bulls that reside in Australia are sired by bulls from the USA. This is an example of the power of AI as a technology and its impact on genetic change in purebred cattle herds, which in turn produce the bulls that are used in much of the commercial cattle industry. To emphasize the impact of AI on genetic change, one Angus bull in the USA produced over 8000 calves in Australia. Data indicate that over 75,000 calves were produced in the USA by the top 25 bulls in the recent Angus Sire Summary.

Sexing Semen

Practical applications of this technology to enhancing effectiveness and efficiency in terminal cross beef cattle breeding systems have been included in a previous review article (Hohenboken, 1999). Sexing semen can increase the selection differential (Van Vleck, 1981). If 1% of cows are normally needed for selected dams of bulls to be used for AI, the use of sexed semen would allow the opportunity to select from the top 0.5% of cows to produce the bulls used for AI (Van Vleck, 1981). This would result in an increased intensity of selection of dams to produce the bulls used for AI, which would in turn result in an enhanced selection differential for determining dams of bulls used for AI. There would be some genetic advantage through use of "sexed semen" for breeding approximately half of the genetically superior cows of a herd to produce the heifer offspring for replacement females. We do not believe the impact of this management practice on genetic improvement has been reported. This would in turn allow for breeding the lesser genetically desirable females to bulls so that male offspring or females for another purpose than replacement females to be returned to the herd. There would, therefore, be some impact of use of sexed semen on genetic improvement, but at present, the primary driver for the use of sexed semen is as a management tool to control the sex of offspring and not as a driver for enhanced genetic improvement in cattle. An example of use of sexed semen as a management tool to control gender is to increase the number of heifers produced for milk production in the USA dairy industry. This is a particularly attractive management tool when the cost of dairy heifers is great, such as occurred in the USA when there was closure of the Canadian border in recent years due to detection of a case of Bovine Spongioform Encephalopathy in Canada.

Multiple Ovulation and Embryo Transfer (MOET)

This technique has the potential to obtain more than a normal number of offspring from cows of great genetic value. Embryo transfer technologies, however, are not likely to increase accuracy of predicting genetic value. With less semen needed to produce daughters, fewer daughters per tested bull might result and actually cause a decrease in accuracy of genetic evaluation when embryo transfer is used (Van Vleck, 1981). The primary impact that MOET has on genetic improvement is through further enhancing the selection differential when used in combination with AI. The use of MOET, therefore, decreases the generation interval and increases the rate of genetic improvement by approximately 30% compared with conventional breeding methods involving progeny testing (Villanueva et al, 1995).

This technology has been used to import and export superior genetics into and out of the USA, and thus is a valuable technology for spreading the superior genetics of beef cattle worldwide. An example of this is what has occurred in one of the leading Angus herds in the USA, where the top 10% of the 2- and 3-year old cows produced 80% of the calves in the herd (personal information, R. Wallace – Select Sires AI Stud, Plain City, Ohio USA).

Cloning and Transgenesis

Each clone is genetically a duplicate. Records indicating genetic value should be obtained over many years before selecting an animal that is to be cloned for purposes of genetic improvement. The reason is that apparently outstanding cows from a productivity perspective may be environmentally produced freaks of nature as a result of low probability environmental factors becoming aligned during prenatal and postnatal development, resulting in unique gene expressions from these epigenetic actions that would have a low probability of occurring in the normally distributed population. According to Van Vleck (1981), the expected genetic superiority of the clone would account for about 25% of the superiority of the records. Genetic diversity, however, could be detrimentally impacted if only a few cows are cloned to be used in the entire industry. The genetic variability could be reduced, therefore, to the extent that environmental adaptation could be detrimentally impacted.

Cloning via somatic cell genetic transfer combined with transgenesis could have an important role in genetic improvement because of the increased accuracy of selection and rapidity of dissemination of the introduced gene. A problem with cloning is that the original great genetic increase from cloning, of the most select animals, would result in a one time boost in genetic improvement, but after having accomplished this, other technologies such as AI would have to be used to make subsequent genetic progress. Furthermore, the commercial sector often believes there is no great advantage to cloning an animal for increased production of spermatozoa from a specific bull for use in AI, because number of spermatozoa produced is not typically a limiting factor for use of bulls in the beef industry.

Summary

The reproductive technology with the greatest potential to enhance rate of genetic improvement is AI. The other reproductive technologies, with the exception of MOET, only have a minor impact on genetic improvement because of technical limitations such as which occurs with decreased fertility and offspring viability with use of these technologies. Other food producing animal sectors have adopted the use of AI to a greater extent than the beef industry. Examples are the commercial turkey (100%), pork (≈ 90%), and dairy (≈ 65%) industries in the USA, where there has been great use of AI. The reason for the high adoption of AI in these industries is to enhance the selection differential for one or a few highly desired traits. The structure of the beef industry is such that use of AI for genetic improvement has not occurred to the extent that it has in these other food producing animals despite the superior AI technologies available for use in cattle as compared with the other food producing animals. One reason for this lesser AI adoption rate is the lack of focus in this industry on one or a few highly heritable and desirable traits. This technology has, therefore, been used in the beef industry in a manner that has not increased inbreeding to the extent that detrimental impacts such as decreased reproduction have occurred. Up until the last decade, the use of AI was minimal in the pork industry in the USA. During the last decade there has been tremendous increase in the use of AI so as to control the genetic composition of the pigs that produce pork. This has occurred even though the techniques for collecting, storing, and use of semen for AI are developed to a much lesser extent for pigs than cattle. The authors, therefore, hypothesize that there will be a time in the future when changes in market demand will cause a dramatic change in the need to control genetics of beef cattle which will ultimately result in greater use of the reproductive technologies, particularly AI, in the beef industry. This will particularly be the situation where there is a desire to produce niche beef products that have specific quality characteristics.

References

Basrur, P.K., and King, W.A., 2005. Genetics then and now: breeding the best and biotechnology. Rev. Sci. Tech., 24:312-49.

Betteridge, K.J., 2003. A history of farm animal embryo transfer and some associated techniques. Anim. Reprod. Sci., 79:203-244.

Bradley, D.G., Loftus, R.T. Cuuingham, P., and MacHugh, D.E., 1998. Genetics and domestic cattle origins. Evol. Anthropol., 6:79-86.

Evans, G., 1991. Application of reproductive technology to the Australian Livestock Industries. Reprod. Fertil. Dev., 3:627-650.

First, N.L., Mitalipova, M., and Kent M., 1999. Reproductive technologies and transgenics. In: The Genetics of Cattle (R. Fries and A. Ruvinsky, eds). CABI Publishing, New York. 411-436.

Foote, R.H., 2002. The history of artificial insemination selected notes and notables. J. Anim. Sci. 80:(Suppl. 2):10.

Harlizius, B., Hetzel, J., and Berendse, W., 1995. Comparative mapping of the proximal part of the bovine chromosome 1. Mammalian Genome, 6:481-483.

Hohenboken, W.D., 1999. Applications of sexed semen in cattle production. Theriogenology, 52:1421-1433.

Maxwell, W.M.C, Evans, G., Hollinshead, F.K., Bathgate, R., de Graaf, S.P., Eriksson, B.M., Gillan, L., Morton, K.M., and O'Brien, J.K., 2004. Integration of sperm sexing technology into the ART toolbox. Anim. Reprod. Sci., 82-83:79-95.

Sartori, R., Souza, A.H., Guether, J.N., Caraviello, D.Z., Geiger, L.N., Schenk, J.L., and Wiltbank, M.C., 2004. Fertilization rate and embryo quality in superovulated Holstein heifers artificially inseminated with X-sorted or unsorted sperm. Anim. Reprod., 1:86-90.

Seidel, G.E., 2003. Sexing mammalian semen – intertwining of commerce, technology, and biology. Anim. Reprod. Sci., 79:145-156.

Seidel, G.E., Schenk, J.L., Herickhoff, L.A., Doyle, S.P., Brink, Z., Green, R.D., and Cran, D.G., 1999. Insemination of heifers with sexed semen, Theriogenology 52:1407-1420.

Tubman, L.M., Brink, Z., Suh, T.K., and Seidel, G.E., Jr., 2004. Characteristics of calves produced with sperm sexed by flow cytometry/cell sorting. J. Anim. Sci. 82:1029-1036.

Van Vleck, D., 1981. Prenatal genetic impact of artificial insemination, sex selection, embryo transfer, cloning and selfing in dairy cattle. In: New Technologies in Animal Breeding (B. Brackett, G. Seidel Jr., and S. Seidel). Academic Press, New York. 221-242.

Villanueva, B., Simm, B., and Woolliams, J.A., 1995. Genetic progress and inbreeding for alternative nucleus breeding schemes for beef cattle. Anim. Sci. 61:231-239.