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14. ABSTRACT

This study investigated the carcinogenic and immunotoxic potential of embedded fragments of depleted uranium (DU) and a heavy-metal tungsten alloy (WA) consisting of tungsten, nickel, and cobalt. Male Fisher 344 rats were surgically implanted with pellets of DU, WA, tantalum (inert metal, negative control), or nickel (known carcinogen, positive control). Implanted WA resulted in the rapid formation of tumors, identified as rhabdomyosarcomas, surrounding the pellets. These tumors had, within the same area, histopathological characteristics of both the pleomorphic and embryonal subtypes of rhabdomyosarcomas. Eventually these tumors metastasized to the lung. Rats implanted with tantalum or DU pellets did not develop tumors at the implantation site. In addition, WA-implanted rats (high-dose group) exhibited splenomegaly and hematological changes suggesting polycythemia as early as 1 month after pellet implantation.

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Table of Contents

INTRODUCTION

Advancement in weapons design has led to the introduction of several potentially toxic metals, such as depleted uranium (DU), onto the battlefield. The Persian Gulf War in 1991 saw the first combat use of DU kinetic penetrator munitions, and their success against enemy armor was dramatic. The demonstrated effectiveness of DU munitions in the first Gulf War has led other nations, some not friendly to the United States, to adopt these weapons into their own arsenals. Other types of kinetic energy penetrators use heavy-metal tungsten alloys (WA) in place of DU. In future conflicts, the United States will have to deal with an increased number of casualties from the use of these weapons. Because both DU- and WA-based munitions are relatively recent additions to the list of militarily relevant metals, little is known about the health effects of these metals after internalization as embedded shrapnel. This study was designed to assess the carcinogenic and immunotoxic potential of DU and WA using the Fisher 344 rat model and modified National Toxicology Program protocols for such studies. Responses to the test metals were compared to responses to tantalum, a biologically inert metal that serves as a negative control and nickel, a known heavy-metal toxin and carcinogen that serves as a positive control. This research addresses the DOD effort to understand the potential health risks associated with DU and WA exposure in order to develop appropriate medical treatment protocols for personnel wounded by fragments of these metals.

BODY

Statement of Work

This study is an assessment of the immunotoxic and carcinogenic potential of embedded fragments of DU and WA in laboratory rats. Responses to these metals are compared to the biologically inert metal, tantalum, and the carcinogen and heavy-metal toxin, nickel. For these experiments, rats are implanted with tantalum pellets alone (metal control group), a mixture of DU and tantalum pellets (low DU group), DU pellets alone (high DU group), a mixture of WA and tantalum pellets (low WA group), or WA pellets alone (high WA group). There is also a non-surgical control group and a positive carcinogenesis control group implanted with nickel pellets. Animals will be euthanized and various analyses performed 1, 3, 6, 12, 18, and 24 months after implantation. Analyses include histopathological examination and metal determinations as well as assessments of mutagenicity and cytogenicity. A battery of immunological tests designed to assess both humoral and cell-mediated immunity, as well as the innate immune response, will be conducted at 1, 3, 6, and 12 months.

Progress to Date

This is the final report for this project. All five tasks associated with the project have been successfully completed. Research results for most of the task areas have been presented in detail in previous annual reports. In order to provide an overview of the project, the tasks and the corresponding results are summarized below.

Task 1 - *Determine whether embedded fragments of DU or WA cause cancer in rodents.*

General health parameters

Change in body weight is considered one of the sensitive, early indicators of change in overall health. The animals in this study were weighed weekly and data presented in the Year 3 Annual Report. In the week immediately after pellet implantation, there was no or only a very slight gain in body weight as the animals recovered from surgery. After this recovery period, animals in all groups gained weight at a consistent rate for the next month. After that time, rodents in the high-dose DU group gained weight at a slower rate than the other experimental

groups. This decreased rate of body weight gain continued throughout the lifespan of the rat. A similar effect for DU was reported previously for Sprague-Dawley rats (Pellmar et al., 1999).

Hematological and serum clinical chemistry data were collected for all experimental groups and reported in the Year 3 Annual Report. Several results are noteworthy. Rats implanted with 20 WA pellets exhibited significant increases in white blood cell counts, red blood cell counts, hemoglobin, and hematocrit levels compared to control rats, while rats implanted with 20 Ni pellets had significant decreases in red blood cell counts, hemoglobin, and hematocrit levels. Hematological parameters from low-dose WA rats were not statistically different from controls. The hematological changes observed in the high-dose WA rats are suggestive of polycythemia. Cobalt has been used experimentally to induce polycythemia in rats (Rakusan et al., 2001; Endoh et al., 2000) although the concentration required is far greater than found in the WA pellets. The speed at which these hematological changes occurred in the high-dose WA rats was also surprising. Statistically significant increases in red blood counts, hemoglobin, and hematocrit levels were observed in high-dose WA animals as early as one month after pellet implantation and persisted throughout the experimental period. In addition, there were statistically significant increases in the numbers of neutrophils, lymphocytes, monocytes, and eosinophils present in high-dose WA animals. Low-dose WA animals had elevated neutrophil, lymphocyte, and monocyte numbers, but only the neutrophil numbers were statistically different from the controls. The Ni-implanted animals had significantly lower lymphocyte counts than the controls. All other parameters were statistically identical to the controls. These results suggest a dose-dependent perturbation in many hematology parameters as a result of an increasing WA pellet number.

Metal effects on specific organ systems can often be assessed by measuring organ/body weight ratios. The organs assessed were spleen, thymus, liver, kidney, and testes. Data were presented in the Year 3 Annual Report. Low-dose DU animals showed an increase in kidney/body weight ratio, compared to control, at 1- and 3-months post-implantation. However, by 6 months the ratio had returned to normal and remained there for the duration of the experiment. Surprisingly, the high-dose DU groups did not show these kidney changes, but did show decreases in liver/body weight ratios starting at 3 months post-implantation. These changes persisted throughout the duration of the experiment. The most remarkable changes were

seen with the high-dose WA group. Starting at 1 month post-implantation, these animals had extremely elevated spleen/body weight ratios until they were euthanized at approximately 20-24 weeks. In addition, beginning at 3 months post-implantation, kidney/body weight ratios were also elevated.

Carcinogenicity

No tumors at the pellet implantation site, were observed in the tantalum, low DU, or high DU groups at the 1-, 3-, 6-, 12-, 18-, or 24-month time points. The 18- and 24-month animals, in all surviving groups, exhibited health problems associated with old age (e.g., testicular cancer, abdominal growths, etc.). These health problems were not associated with a particular treatment group. They were found across all experimental groups. As a result of these age-related health problems, many of the 18- and 24-month animals were euthanized before reaching their experimental endpoint; however, no abnormalities associated with the tantalum or DU implanted pellets were observed. For the 18-month group, approximately 60 – 70% of the rodents reached the experimental endpoint. Only one rodent (a high-dose DU rat) reached the 24-month experimental endpoint. A table showing survival data for all experimental groups is found in the Appendices (Table 1).

While all the rodents in the non-surgical, tantalum, and DU groups either reached their experimental endpoint or were euthanized due to age-related maladies, the same cannot be said for the WA and nickel groups. By 14-18 weeks after implantation, many of the animals began to develop palpable tumors at the pellet implantation sites. All animals in the low WA, high WA, and nickel groups eventually developed tumors and were euthanized. Criteria for euthanasia is based upon previously published standards (Tomasovic et al., 1988). The high WA group survived the shortest time, with the nickel and low WA groups only slightly longer. Upon euthanasia, the pellets were removed and showed apparent oxidation, but had lost only about 5 % of their mass during implantation. Gross necropsies showed tumors surrounding the WA or nickel pellets. The tumor appeared to displace and replace the skeletal muscle surrounding the pellet. Metastases were invariably found in the lungs of both the low and high WA groups with additional growths occasionally found in the abdominal cavity.

In many cases the leg tumors would undergo rapid aggressive growth, more than doubling their size in a matter of days. There was little or no capsule formation around the WA

pellet or associated tumors (Fig. 1 – Appendices). The tumor infiltrated into the skeletal muscle, separating and isolating individual myofibers. Eventually degeneration of the myofibers , with internalization of nuclei, was observed. Cell pattern and morphology was variable, even within the same tumor. Cell patterns ranged from distinct spindle cell in streams with strap-like cells to pleomorphic spindle cell pattern, to a round cell, spider cell and giant cell patterns, more similar to embryonal rhabdomyosarcomas. Fig. 2 (Appendices) shows characteristics of both pleomorphic and embryonal rhabdomyosarcomas in the same field. Tumors formed only around WA and Ni pellets, a condition dramatically illustrated in Fig. 3 (Appendices).

Tumors observed during gross necropsy are categorized in Table 2 (Appendices). All WA-implanted rats developed tumors at the pellet implantation sites and in many cases these tumors metastasized to the lungs and occasionally through the abdominal cavity. Many of the 18- and 24-month non-surgical, tantalum, and DU (both low and high dose) rats developed interstitial cell tumors of the testes, as well as abdominal growths identified as chronic nodular granulomatous steatitis. Several DU rats also had adrenal (adrenal medullary) and renal tumors (tubule carcinoma, mesenchymal tumor).

As also reported in the Year 3 report, rats implanted with 20 pellets of WA (high dose group) exhibited characteristics of polycythemia (elevated red blood cell counts, splenomegaly). Histopathologic analysis of the spleens from these rats demonstrated a noticeable increase in nucleated red blood cells and a mild decrease in the myeloid:erythroid ratio in the red pulp indicative of eyrthroid hyperplasia.

Task 2 - *Measure tissue levels of DU or WA after chronic in vivo exposure.*

Levels of cobalt, nickel, tungsten, tantalum, and uranium were determined in a variety of tissues (urine, kidney, serum, liver, spleen, muscle) using inductively coupled plasma mass spectrometry (ICP-MS). These data are presented in the Appendices (Figs. 4-45). Most surprising was the rate at which all three alloy metals (Co, Ni, W) appeared in the urine, particularly tungsten which has been assumed to be relatively insoluble. Maximum urine levels of all three metals were found in the 1 month group, with slightly lower levels found in the 3- and 6-month samples. This indicates that, as with uranium, urine metal levels may prove to be an excellent indicator of exposure to WA. As might be expected, kidney levels of all metals

were elevated, showing a dose- and time-dependence. Serum levels of cobalt, nickel, and tungsten mirrored the pattern seen for urine from WA-implanted animals. Serum metal analysis may also prove to be a good indicator of exposure. DU was only present at very low levels in the serum, supporting results obtained by others. Both liver and spleen contained all three of the alloy metals, with significantly high values for tungsten at the 6 month time point. DU was present at very low levels in both spleen and liver. Muscle (gastrocnemius, sampled close to the implantation sites) metal levels were also very low for all metals indicating very little diffusion of the metals through the muscle.

Task 3 - *Assess the genotoxicity and mutagenicity after chronic in vivo exposure to DU or WA.*

Genotoxicity assessments of peripheral blood lymphocytes and serum and urine mutagenicity measurements were conducted. Examination of chromosomal aberrations in peripheral blood lymphocytes suggests that embedded WA or DU is not genotoxic. There was also no indication that serum from any of the experimental groups at the four timepoints measured (6, 12, 18, and 24 months) was mutagenic when assayed by the Ames bacterial reversion assay. However, urine from the high-DU and high-WA groups was significantly more mutagenic than urine from non-surgical or tantalum implanted rats. This result was not unexpected as one of the major routes of excretion of these metals from the body is in the urine. No urine was collected from the 18- and 24-month animals because, due to the declining health of the rodents, we opted against stressing the animals further by housing them in the metabolic cages required for urine collection.

Task 4 - *Determine the effect of embedded DU and WA on the organs of the immune system.*

Assessments for this task included immune organ/body weight ratios, immune organ cellularities, hematological assessments, and flow cytometric analysis of peripheral blood, splenocytes, and thymocytes. Fisher 344 rats implanted with 4 (low dose) or 20 (high dose) pellets of DU or WA were assessed at 1, 3, 6, and 12 months post-implantation. (Note: Because of aggressive tumor formation in the WA-implanted rats, no animals survived to 12 months).

Detailed descriptions of the data concerning this task were presented in the Year 3 Annual Report.

Immune Organ/Body Weight Ratio

Organ/body weight ratios are often sensitive indicators of toxicity. Fisher 344 rats implanted with 4 (low dose) or 20 (high dose) pellets of DU showed no significant differences in spleen/body weight or thymus/body weight ratios when compared to control rats. Rats implanted with 20 pellets (high dose) of WA showed significantly higher spleen/body weight ratios than control rats, indicating splenomegaly. The spleen/body weight ratios of rats implanted with 4 pellets (low dose) of WA, although elevated, were not statistically different then control rats. The thymus/body weight ratios of WA-implanted rats were not significantly different than control rats, with the exception of the high-dose WA group at 5-6 months post-implantation.

Immune Organ Cellularity

The number of cells per gram of spleen and thymus, as well as the number of bone marrow cells per femur, were determined. For WA- implanted rats, spleen cellularity at 1 month post-implantation was significantly lower than in control rats in both the low- and high-dose groups; however, these numbers returned to normal by 3 months post-implantation. Thymus cellularity in WA-implanted animals was no different than controls, except for the 6 month low-dose group, and there were no differences in bone marrow cellularities in any of the WA groups when compared to control. Low-dose DU implanted rats showed lower splenocyte and thymocyte counts at 6 months post-implantation, although the high-dose DU implanted rats did not show these decreases. However, bone marrow counts in both low- and high-dose DU rats were significantly lower starting at 3 months post-implantation and stayed lowered throughout the 12 month experimental time course.

Hematology

Complete hematologic assessments were conducted on all animals. DU-implanted rats showed very few significant and lasting changes. Low-dose DU rats had higher white blood cells and lymphocyte counts (compared to control) at 1 month post-implantation. However, these numbers were then lowered than control at the 3 month timepoint. Neutrophil counts were also lower in low-dose DU rats at 3 months. By 6 months post-implantation, these values had

returned to normal. In high-dose DU rats, platelet counts were elevated, compared to control, at both 1 and 3 months post-implantation. They returned to normal at 6 month; however, both white and red blood cell counts, as well as hematocrit levels, were depressed. These values returned to normal at 12 months post-implantation. In both the low- and high-dose DU rats, platelet values were lower than control at 12 months post-implantation.

A variety of hematological changes were observed in WA-implanted rats. For low-dose WA rats, the hematological changes, including significant increases in red blood cells, white blood cells, hemoglobin, hematocrit, neutrophils, lymphocytes, and monocytes, peaked at 3 months post-implantation and returned to normal by 5-6 months. High-dose WA rats demonstrated the same changes observed in low-dose WA rats, but they occurred much more rapidly (as early as 1 month post-implantation) and persisted throughout the life of the animal. The splenomegaly and hematological changes observed in these rats are suggestive of polycythemia. These results suggest a dose-dependent perturbation in many hematology parameters as a result of an increasing WA pellet number.

Flow cytometry

Flow cytometric analysis of peripheral blood lymphocytes, splenocytes, and thymocytes was conducted in order to investigate any changes, as a result of prolonged exposure to embedded DU or WA, in the subpopulations of cells that comprise these immune system organs. Using the methods of Flaherty et al. (1997) and Capri et al. (2000), the CD4 and CD8 subpopulations in isolated thymocytes; the cytotoxic T-cell, T-helper cell, and the naïve and activated subpopulation of CD4 and CD8 cells in peripheral blood; and the T cell, B cell, cytotoxic T cell, T helper cell, NK cell, and putative monocyte levels in isolated splenocytes were determined.

For DU-implanted rats, the number of splenic NK cells were decreased 1 month post-implantation, but had returned to normal by 3 months post-implantation. All assessments at every other time point were not statistically different than control, with the exception of the 6-month splenic NK cells for the low-dose DU group which were significantly higher than control. However, at 12 months post-implantation there was no significant difference and the high-dose DU group showed no such changes.

For WA-implanted rats, there were numerous and consistent changes in immune cell subpopulations in both peripheral blood and spleen. High-dose WA-implanted rats showed significant decreases in peripheral blood cytotoxic T cells, T helper cells, and naïve CD4 and CD8 cells starting as early as 1 month post-implantation. Both the low- and high-dose WA rats demonstrated lower splenic B cell levels, as well as lower NK cell levels (as did both DU groups) at 1 month post-implantation. The peripheral blood subpopulation changes persisted in the high-dose WA rats at 3 months post-implantation. The splenic B cell levels returned to normal in both WA groups, but splenic NK cell levels remained depressed. By 6 months post-implantation, all WA rats had developed tumors at the pellet implantation site and were reaching the criteria for euthanasia. Not surprisingly, all peripheral blood flow cytometric parameters were significantly lower in both the low- and high-WA animals as compared to control. Somewhat surprisingly, values for the various immune system cell subpopulations in the spleen were not statistically different from control, except for splenic NK cell levels which had risen significantly higher. As noted earlier, no WA animal survived to the 12 month time point.

Task 5 – *Evaluate the effect chronic in vivo exposure to DU and WA has on immune function, including cell-mediated, humoral, and innate immunity.*

This task was completed and results reported in the Year 3 annual report. Three tests of immune function were conducted: the cytotoxic T-lymphocyte assay, the Natural Killer (NK) cell assay, and the antibody plaque-forming cell assay.

Cytotoxic T-Lymphocyte Assay

Cytotoxic T-lymphocytes (CTL) are an important component of the adaptive immune response, especially with respect to intracellular pathogens. In low-dose DU implanted rats, CTL activity is no different than control at 1 month post-implantation, is elevated at 3 months, slightly depressed at 6 months, and returns to normal at 12 months post-implantation. In high-dose DU rats, CTL activity is slightly depressed at 6 months post-implantation, but is no different than control at all other times. In low-dose WA rats, CTL activity is no different than control at 1 and 3 months post-implantation, but is lower at 6 months (the final time point assayed). Similar results are seen for high-dose WA rats except they also exhibit depressed CTL activity at 3 months post-implantation.

Natural Killer Cell Assay

Natural killer (NK) cells are lymphocytes involved in the early immune response to both viral pathogens and malignant transformation. In rodents, NK activity is highest when the rats are young and rapidly decreases to non-detectable levels later in life. We also found that in this study. There was no detectable NK activity at the 6- and 12-month timepoints. In low-dose DU rats at 1 month post-implantation, NK activity is below that of control rats. At 3 months, NK activity is still low but it is not statistically different than control. In high-dose DU rats, NK activity is normal at 1 month, but lower than control groups at 3 months post-implantation. In both low- and high-dose WA rats, NK activity is significantly depresses compared to control rats at both the 1 and 3 month timepoints.

Antibody Plaque-forming Cell Assay

The antibody plaque-forming cell assay (APC) measures the ability of the animal to elicit an antibody response to a foreign antigen. It is considered the "gold standard" test for immunotoxicity assessments. In DU-implanted rats, APC activity was no different than control except for two points: the 12 month point for low-dose DU rats and the 6 month point for high-dose DU rats were both lower than control groups. For WA rats, the low-dose group was no different than control at 1 month, but then exhibited elevated APC activity at 3 and 6 months post-implantation. (No rats survived to the 12 month timepoint). For high-dose WA rats, APC activity was no different than control at 1 month, but then was significantly elevated at 3 months post-implantation.

KEY RESEARCH ACCOMPLISHMENTS

- All animals implanted with WA (both low and high groups) or nickel developed tumors, identified as rhabdomyosarcomas, at the implantation site.
- Tumor development occurred most rapidly in the high WA group.
- Tumors metastasized to the lung in both the low and high WA groups.
- Histopathological examination showed that the tumors exhibited characteristics of both classical or pleomorphic rhabdomyosarcomas as well as embryonal rhabdomyosarcomas.
- No pellet-associated tumors were found in the tantalum- or DU-implanted animals.

- Significantly high levels of cobalt, nickel, and tungsten appeared in the urine and serum of WA-implanted rats as early as one month after pellet implantation.
- Rodents in the high WA group exhibited splenomegaly and hematological changes suggesting polycythemia.
- Rodents in the high WA group exhibited altered distribution of lymphocyte subpopulations in both peripheral blood and spleen as early as one month after pellet implantation.

REPORTABLE OUTCOMES

Oral Presentations and Abstracts

Oral presentation (and abstract) by Dr. David McClain at the Force Health Protection Conference (Albuquerque, NM, 11-15 August 2003). Title: Health Effects of Embedded Depleted Uranium and Tungsten Alloy Fragments in Rats.

Oral presentation by Dr. David McClain at the US Army Heavy Metals Office Heavy Alloys Workshop, Stevens Institute of Technology, Hoboken, NJ, 10-11 February 2004. Title: Tumor Induction in Rats by Embedded Tungsten Alloy Fragments.

Oral presentation by Dr. David McClain at the United States/United Kingdom International Exchange Agreement 1443 Workshop (US/UK IEA 1443), US Army Research Laboratory, Aberdeen, MD, 24 June 2004. Title: Tumor Induction in Rats by Embedded Tungsten Alloy Fragments

Oral presentation by Dr. David McClain at the Armed Forces Radiobiology Research Institute Seminar Series, 5 March 2004. Title: Investigation of Tumor Induction in Rats by Embedded Tungsten Alloy Fragments.

Oral presentation by Dr. David McClain at the Armed Forces Radiobiology Research Institute Scientific Program Overview, AFRRI Board of Governors Meeting, 27 July 2004. Title: Investigation of Health Effects of Embedded Tungsten Alloy Fragments in Rats.

Oral presentation by Dr. John Kalinich at the Armed Forces Radiobiology Research Institute Seminar Series, March 19, 2004. Title: Immunotoxic Potential of Militarily Relevant Heavy Metals.

Oral presentation by Dr. John F. Kalinich at the TSCA ITC Meeting, Washington, DC, May 5, 2005. Title: Health Effects of Tungsten Alloys.

Oral presentation (and abstract) by Dr. David McClain at the NATO RTG-099 Meeting, Bethesda, MD, June 21-23, 2005. Title: Status of Health Concerns about Military Use of Depleted Uranium and Surrogate Metals in Armor Penetrating Munitions.

Oral presentation (and abstract) by Dr. David McClain at the 8th Annual Force Health Protection Conference, Louisville, KY, August 7-12, 2005. Title: Embedded Tungsten Alloy Fragment Research and its Implications.

Oral presentation (and abstract) by Dr. John Kalinich at the American Chemical Society 230th National Meeting, Washington, DC, August 28 – September 1, 2005. Title: Embedded Weapons-grade Tungsten Alloy Shrapnel Rapidly Induces Metastatic High-grade Rhabdomyosarcomas in F344 Rats.

Oral presentation by Dr. David McClain at the Military Health Services Tricare Convention, Arlington, VA, 01 February 2006. Title: Carcinogenicity of Embedded Tungsten Alloy in Rats.

Oral presentation (and abstract) by Dr. David McClain and Dr. John Kalinich at the 2006 International Conference on Tungsten, Refreactory and Hardmetals VI, Orlando, FL, 7-8 February 2006. Title: Embedded Weapons-grade Tungsten Alloy Shrapnel Rapidly Induces Metastatic High-grade Rhabdomyosarcomas in F344 Rats,

Oral presentation (and abstract) by Dr. John Kalinich at the U.S. Army Heavy Metals Office's Heavy Metals Forum, Baltimore, MD, 7-9 March 2006. Title: Carcinogenicity of Embedded Tungsten Alloy in Rats – Observations and Outlook.

Oral presentation by Dr. John Kalinich at the Armed Forces Radiobiology Research Institute Seminar Series, March 17, 2006. Title: Health Effects of Embedded Tungsten Alloy Fragments

Oral presentation by Dr. John Kalinich at the Tungsten Hazards Meeting, Picatinny Arsenal, NJ, 21 March 2006. Title: Health effects of embedded tungsten alloy in rats.

Manuscripts

John F. Kalinich, Christy A. Emond, Thomas K. Dalton, Steven R. Mog, Gary D. Coleman, Jessica E. Kordell, Alexandra C. Miller, and David E. McClain, Embedded weapons-grade tungsten alloy shrapnel rapidly induces metastatic high-grade rhabdomyosarcomas in F344 rats, Environmental Health Perspectives **113**: 729-734 (2005).

David E. McClain, Alexandra C. Miller, and John F. Kalinich, Status of health concerns about military use of depleted uranium and surrogate metals in armor-penetrating munitions, Proceedings of the Human Factors and Medicine (HFM) Panel Research Task Group (RTG) 099 Meeting, Bethesda, MD June 21-23, 2005.

Two additional manuscripts are in preparation. Copies will be sent to USAMRMC for the files once the manuscripts are accepted for publication.

Personnel Employed Under This Grant:

Jessica Kordell

CONCLUSIONS

This study investigated the carcinogenic and immunotoxic potential of embedded fragments of depleted uranium (DU) and a heavy-metal tungsten alloy (WA). Male Fisher 344 rats were surgically implanted with pellets of DU, WA, tantalum (inert metal, negative control), or nickel (known carcinogen, positive control). Implanted WA resulted in the rapid formation of tumors, identified as rhabdomyosarcomas, surrounding the pellets. These tumors had, within the same area, histopathological characteristics of both the pleomorphic and embryonal subtypes of rhabdomyosarcomas. Eventually these tumors metastasized to the lung. Rats implanted with tantalum or DU pellets did not develop tumors at the implantation site. In addition, WA-implanted rats (high-dose group) exhibited splenomegaly and hematological changes suggesting polycythemia as early as 1 month after pellet implantation. Tungsten, nickel, and cobalt rapidly appeared in the urine and serum of WA-implanted animals, with significant levels seen as early as one month post-implantation. Urine and serum levels may prove to be reliable indicators of tungsten alloy exposure.

The finding that embedded WA pellets resulted in rapid and aggressive tumor development has raised significant concern since heavy-metal tungsten alloys are being used as replacements for DU in armor penetrators. In fact, many countries, some unfriendly to the U.S., already possess tungsten munitions. As a result, future combat could produce large numbers of U.S. personnel with tungsten fragment injuries with military surgeons not having the best information available to deal with those injuries.

It should be pointed out that the tungsten alloy we used consisted of tungsten, nickel, and cobalt. Other tungsten alloys, tungsten/nickel/iron in particular, are also being used to produce armor penetrating munitions. Because of the lack of information on the health effects of embedded fragments composed of these types of mixtures, investigations on potential tumor development patterns for implanted tungsten/nickel/iron, as well as for the individual metals alone and in various combinations are sorely needed. With these data, a determination of the carcinogenic potential of the individual metals can be made, as well as a determination of any synergistic effects that may occur when the various metal are present together. With these

results, a comparison of the various alloys can be made and the exposure risk put into perspective.

CRITICAL FUTURE INVESTIGATIONS

One important result of this research is that it points out the need for health-effects studies on militarily relevant material prior to deployment to the field. We highly recommend that a screening protocol be implemented to assess potential health effects of new munition material prior to their widespread use. Several research areas that require immediate attention are:

- Carcinogenic and immunotoxic assessment of embedded W/Ni/Co and W/Ni/Fe, as well as the individual metals, in a second rodent species.
- Modeling of the deposition of the alloys metals in the body.
- Assessment of urine and serum metal levels as indicators of exposure to tungsten alloys.
- Determination of the mechanism of WA-induced tumor formation, and more importantly, how rapidly it occurs so that exposure risk can be assessed and potential treatments can be designed.

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APPENDICES

Figure 42 Muscle Uranium Concentrations: 6 Month and 12 Month Groups
Figure 43 Muscle Uranium Concentrations: 18 Month Groups
Figure 44 Muscle Cobalt and Nickel Concentrations over Time
Figure 45 Muscle Tungsten and Uranium Concentrations over Time
Manuscript *Environmental Health Perspectives* **113**, 729-734, 2005.

Table 1. Survival Times of Pellet-Implanted Rodents

Time	Experimental Group	Mean (weeks) ± sem
24 Month	Non-Surgical	83.44 ± 2.05
(104 weeks)	Tantalum	82.69 ± 4.11
	DU-low	85.44 ± 2.82
	DU-high	81.69 ± 3.25
	WA-low	27.13 ± 1.06
	WA-high	21.75 ± 0.37
	Nickel	26.75 ± 0.59
18 Month	Non-Surgical	75.80 ± 1.20
(78 weeks)	Tantalum	74.00 ± 2.70
	DU-low	72.90 ± 2.46
	DU-high	74.30 ± 2.47
	WA-low	25.50 ± 1.83
	WA-high	20.90 ± 0.43
	Nickel	24.80 ± 0.36
12 Month	Non-Surgical	50.70 ± 0.91
(52 weeks)	Tantalum	52.00 ± 0.00
	DU-low	52.00 ± 0.00
	DU-high	52.00 ± 0.00
	WA-low	27.70 ± 0.97
	WA-high	22.25 ± 0.59
	Nickel	23.90 ± 0.31
6 Month	Non-Surgical	26.00 ± 0.00
(26 weeks)	Tantalum	26.00 ± 0.00
	DU-low	26.00 ± 0.00
	DU-high	26.00 ± 0.00
	WA-low	24.85 ± 0.52
	WA-high	22.40 ± 0.53
	Nickel	23.80 ± 0.55
3 Month	Non-Surgical	13.00 ± 0.00
(13 weeks)	Tantalum	13.00 ± 0.00
	DU-low	13.00 ± 0.00
	DU-high	13.00 ± 0.00
	WA-low	13.00 ± 0.00
	WA-high	13.00 ± 0.00
	Nickel	13.00 ± 0.00
1 Month	Non-Surgical	4.00 ± 0.00
(4 weeks)	Tantalum	4.00 ± 0.00
	DU-low	4.00 ± 0.00
	DU-high	4.00 ± 0.00
	WA-low	4.00 ± 0.00
	WA-high	4.00 ± 0.00

Figure 1. Masson Trichrome Stain of WA-Induced Tumor

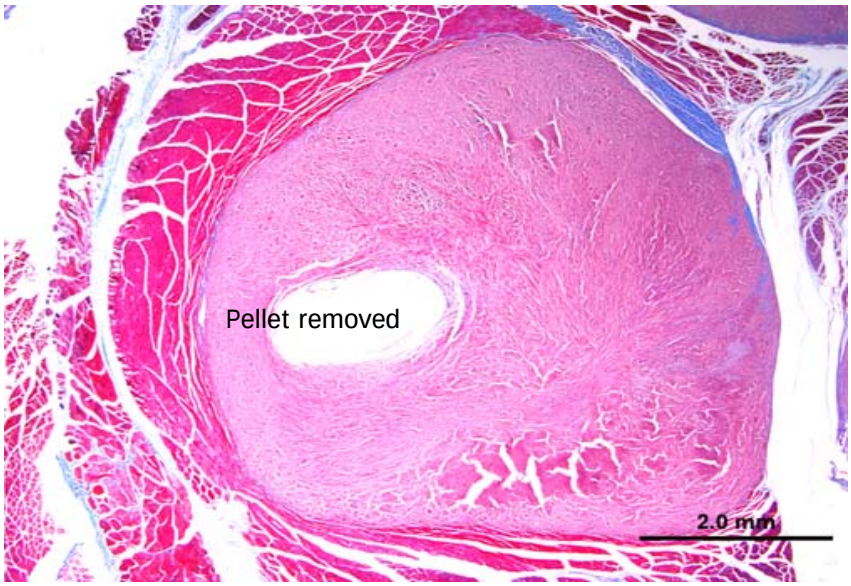


Figure 2. Variable Pattern of WA-Induced Rhabdomyosarcoma Showing Classic or Pleomorphic Rhabdomyosarcoma (lower left corner) and Embryonal Rhabdomyosarcoma (upper right corner)

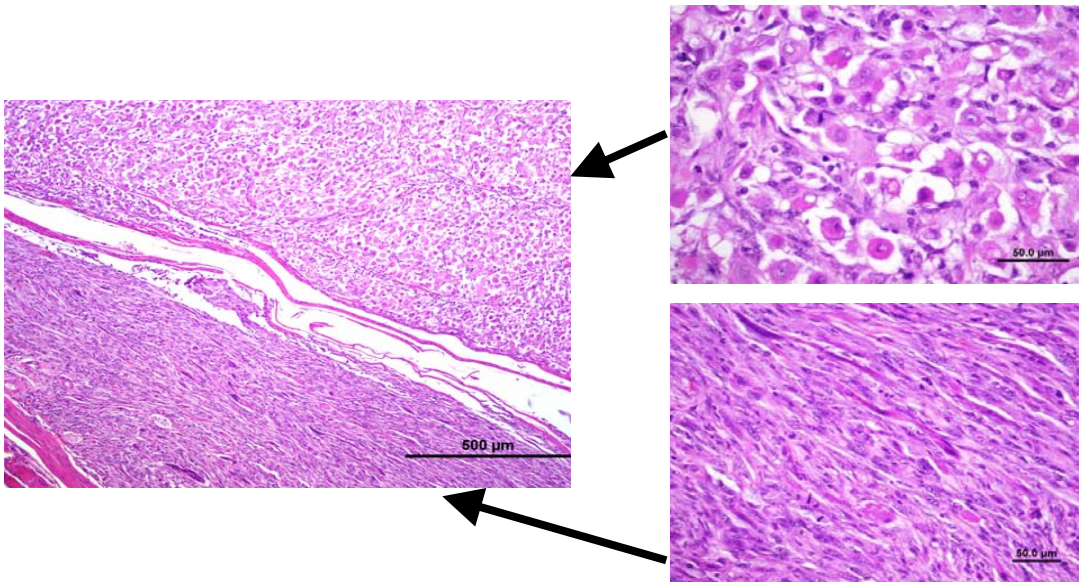


Figure 3. Hematoxylin and Eosin-Stained Section of Pellet Implantation Site from Leg of Rat from 3 Month Low-Dose WA Group. The upper hole was the site of a WA pellet, while the lower hole (with the size bar) contained a tantalum pellet. Note the initial development of neoplastic cells surrounding the WA pellet.

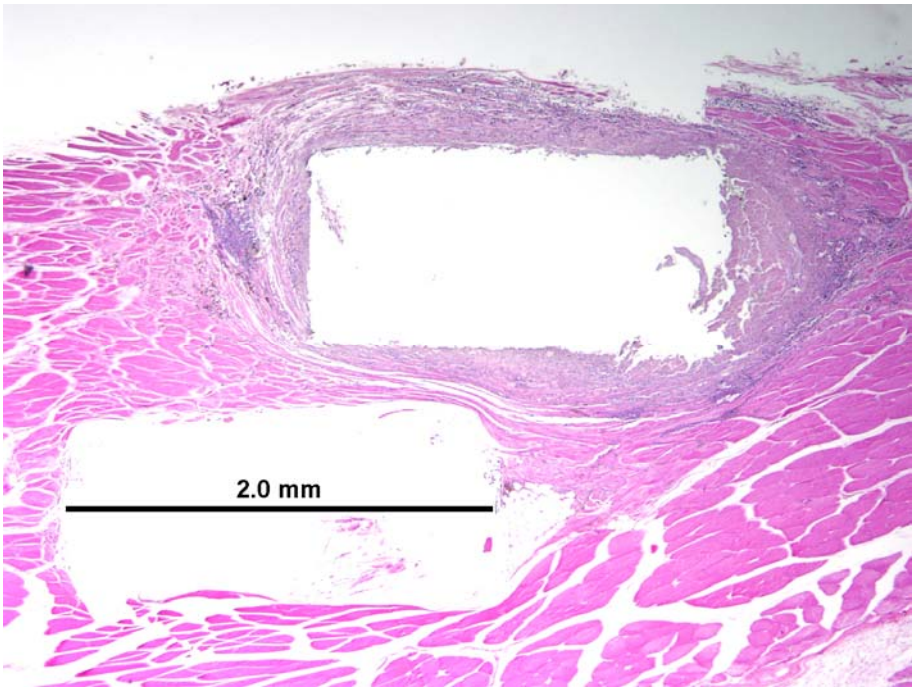
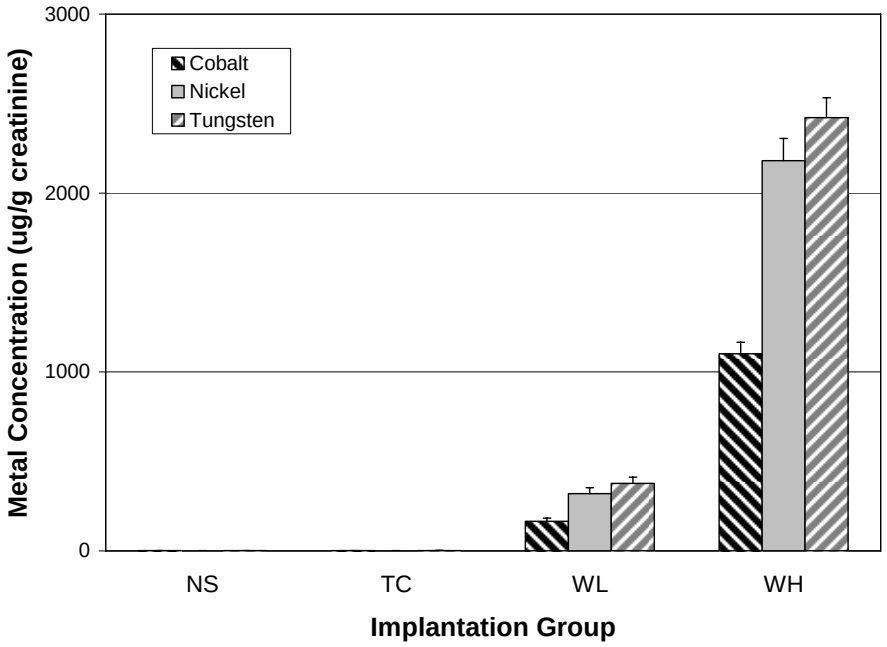


Table 1. Tumor Distribution in Experimental Animals Based on Gross Necropsy Examination.

Time / Group	1 Month (n = 15)	3 Month (n = 15)	6 Month (n = 20)	12 Month (n = 20)	18 Month (n = 10)	24 Month (n = 16)
Non-surgical	None	None	None	1-abdominal	8-testicle	7-testicle 3-abdominal
Tantalum	None	None	2-abdominal	None	8-testicle 2-abdominal	9-testicle 5-abdominal 1-muscle (leg)
DU Low Dose	None	None	None	2-abdominal	8-testicle 1-abdominal	10-testicle 1-abdominal 1-adrenal
DU High Dose	None	None	None	2-abdominal 1-lung	6-testicle 2-abdominal 1-adrenal	9-testicle, 2-lung 5-kidney, 1-muscle (leg)
WA Low Dose	None	None	20-muscle (leg) 2-lung	20-muscle (leg) 2-lung 1-abdominal	10-muscle (leg) 4-lung	16-muscle (leg) 6-lung 2-abdominal
WA High Dose	None	None	20-muscle (leg) 3-lung	20-muscle (leg) 2-lung 1-abdominal	10-muscle (leg) 4-lung 1-abdominal	16-muscle (leg) 6-lung
Nickel	ND	ND	10-muscle (leg) (n = 10)	10-muscle (leg) 1-abdominal (n = 10)	10-muscle (leg) (n = 10)	16-muscle (leg) (n = 16)

A



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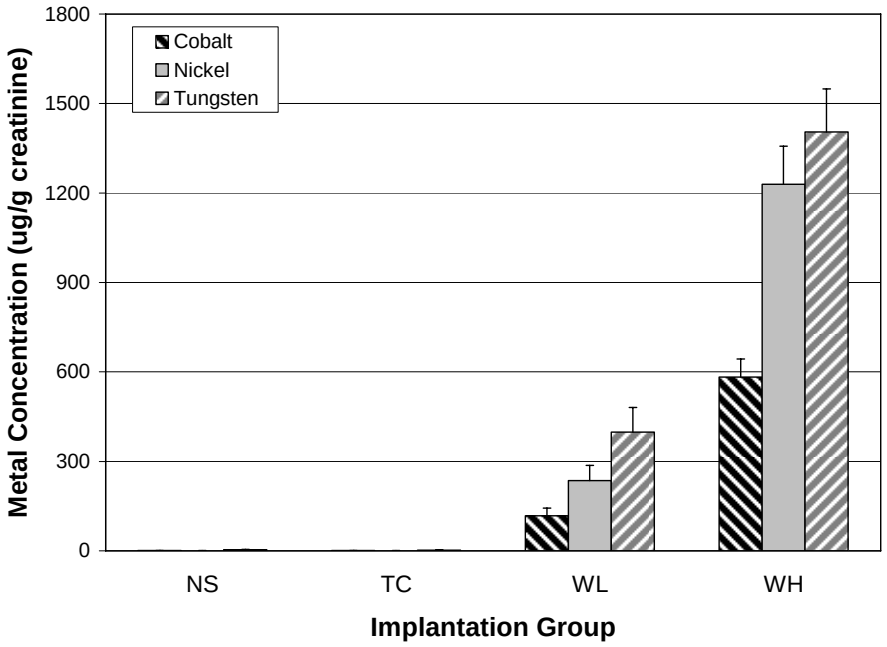


Figure 4. Urine Metal (Co, Ni, W) Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

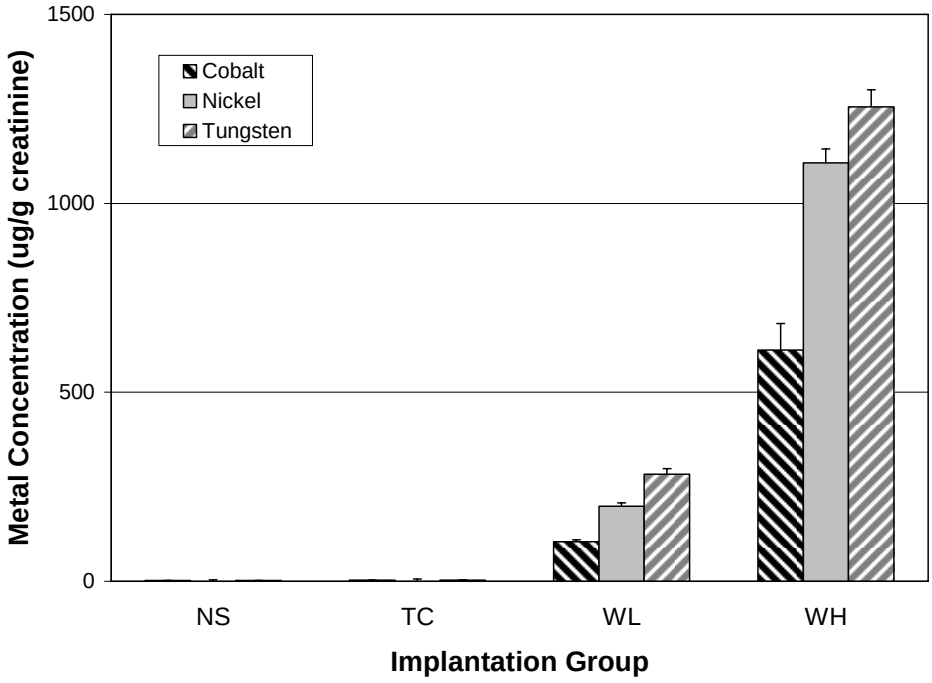
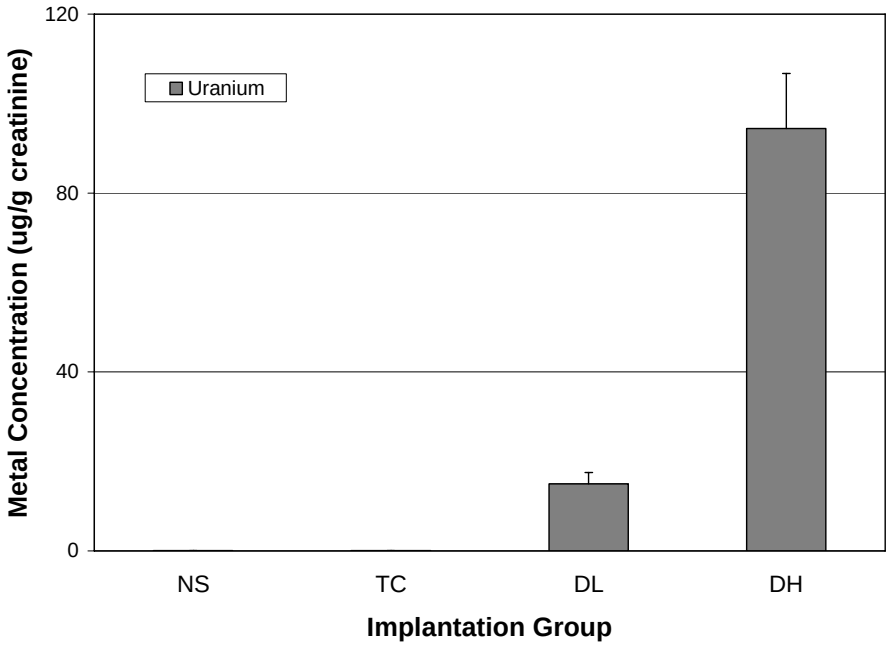


Figure 5. Urine Metal (Co, Ni, W) Concentrations: 6 Month Group. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



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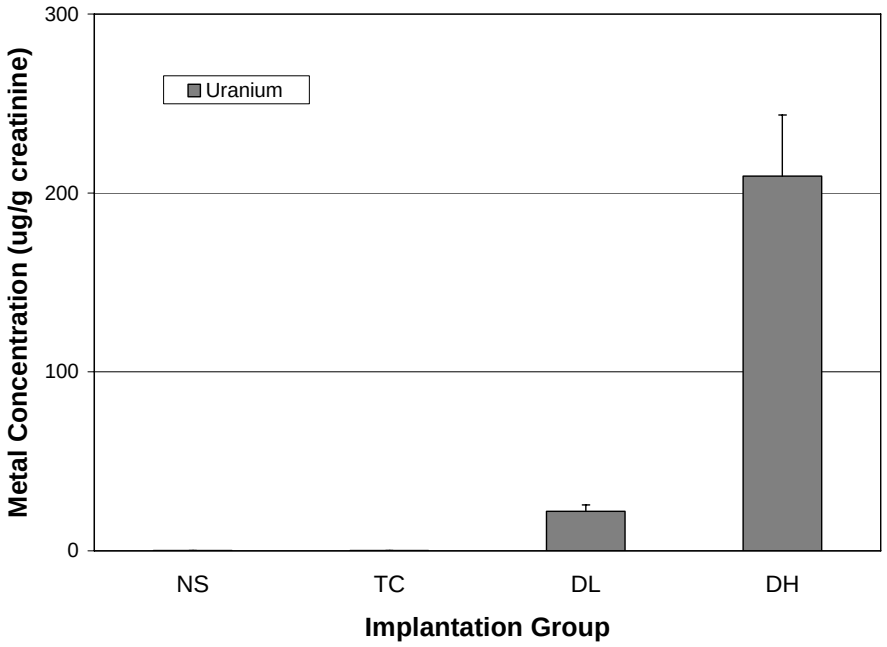
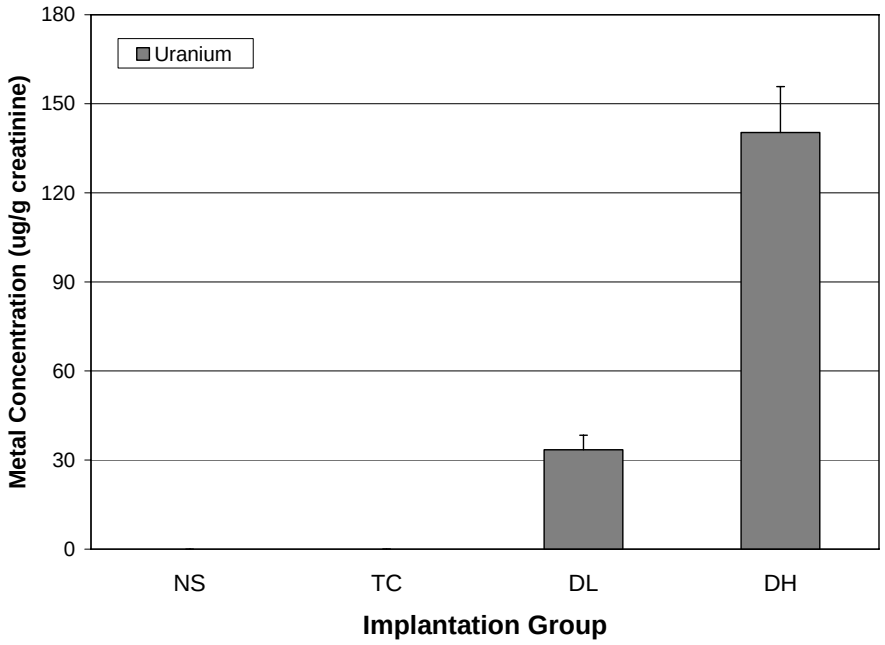


Figure 6. Urine Uranium Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



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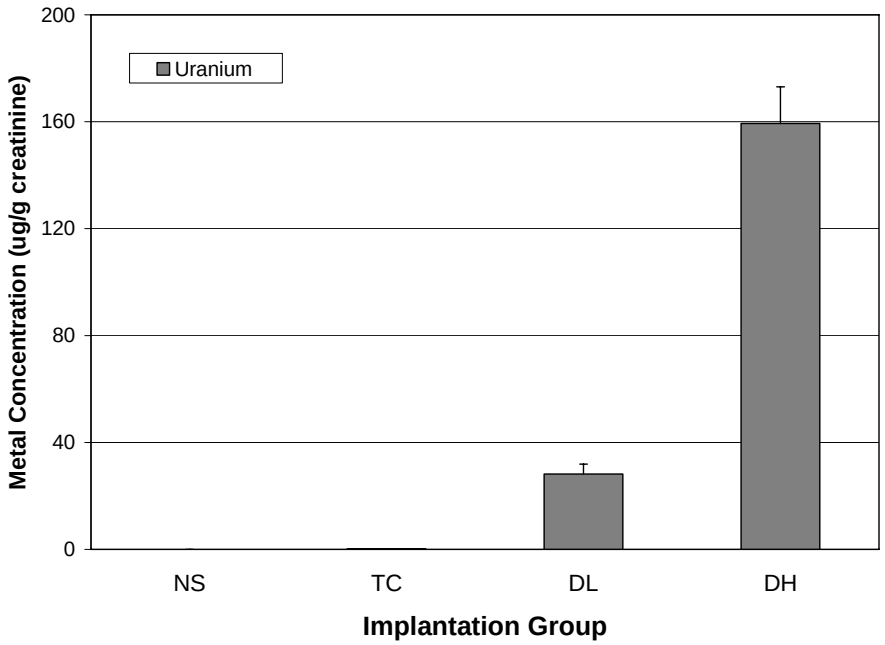


Figure 7. Urine Uranium Concentrations: 6 Month (Panel A) and 12 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

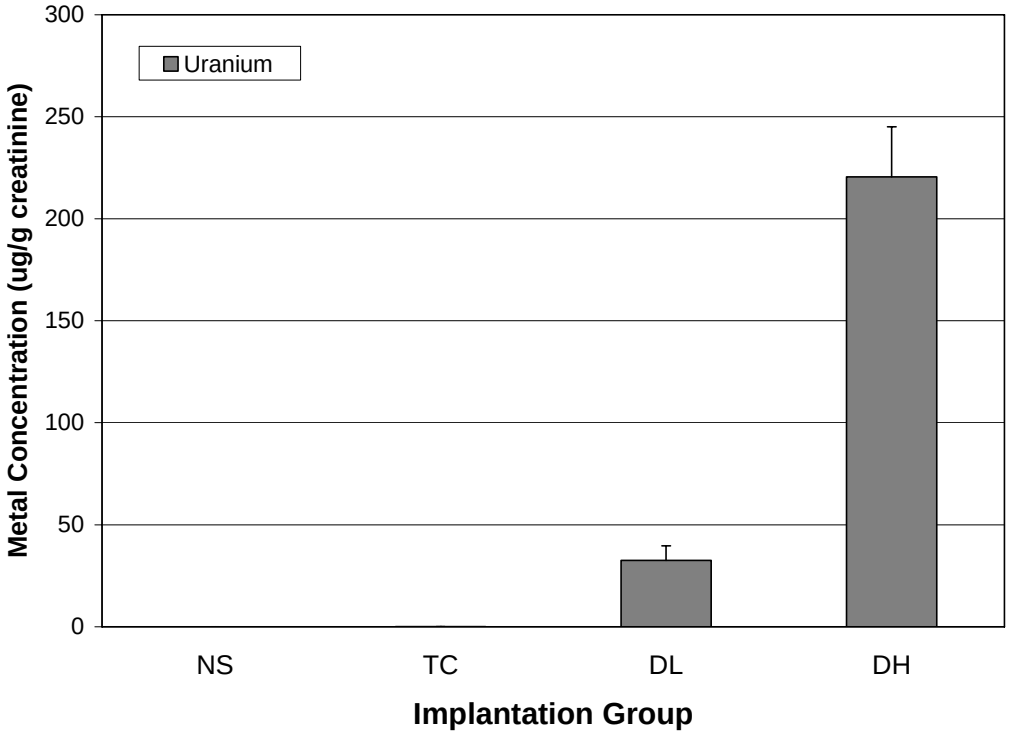
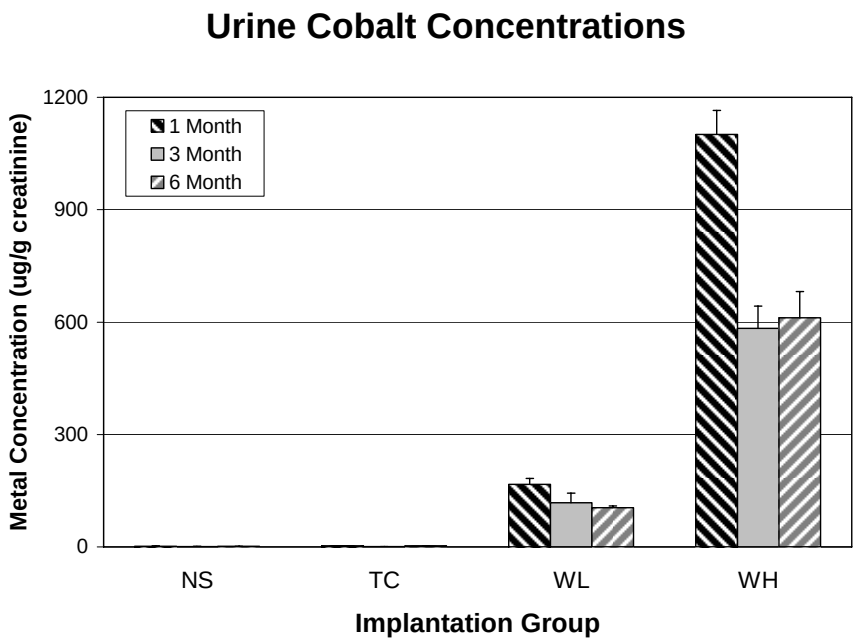


Figure 8. Urine Uranium Concentrations: 18 Month Group. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



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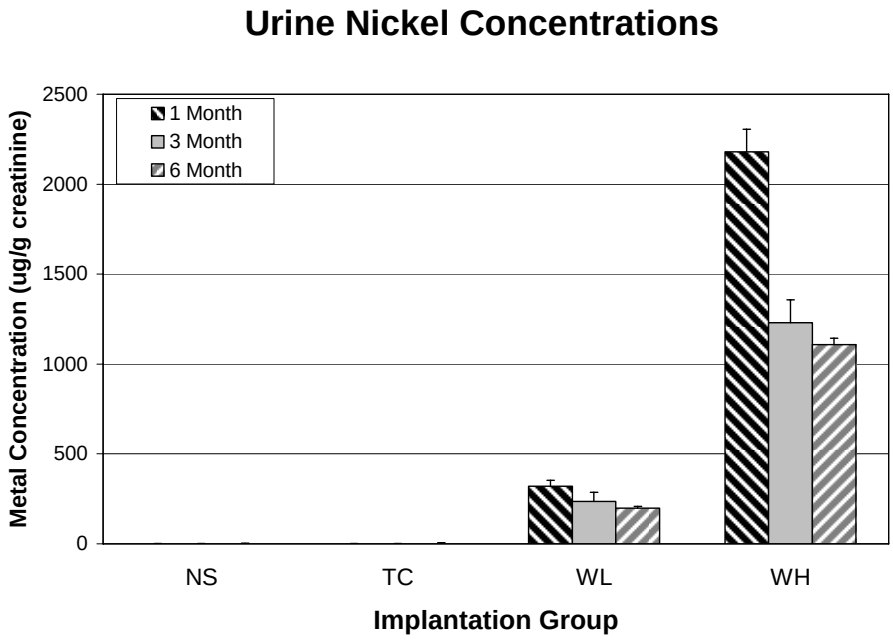
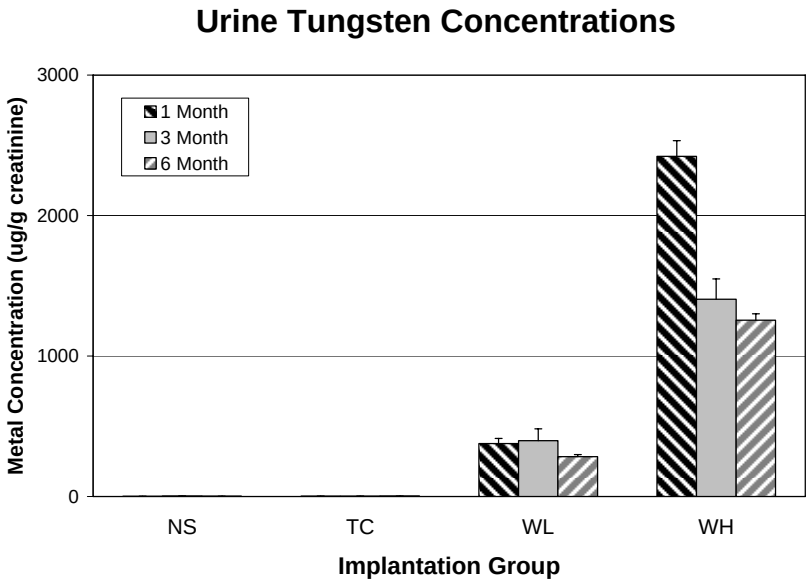


Figure 9. Urine Cobalt (Panel A) and Nickel (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



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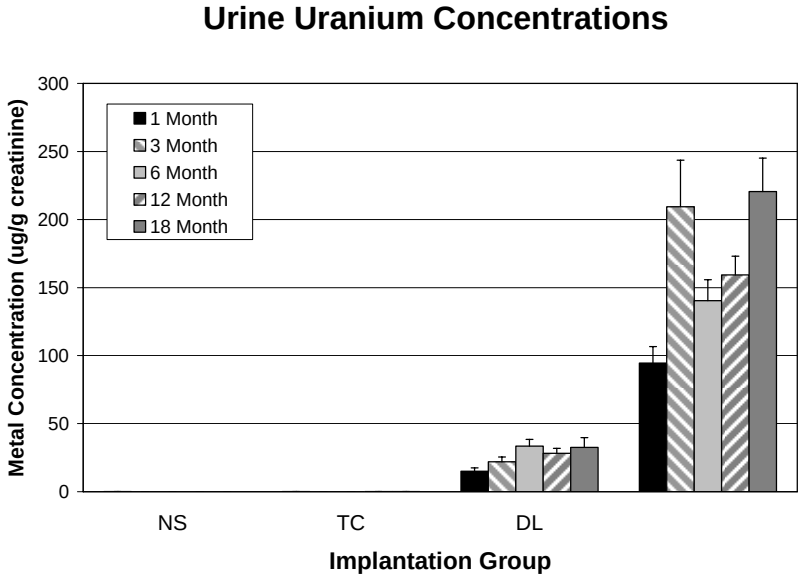
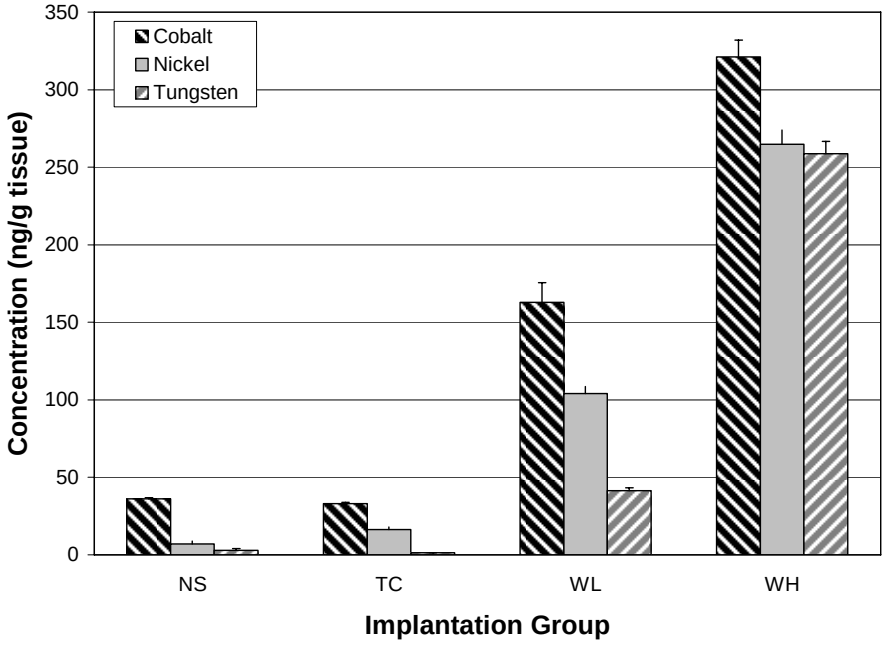


Figure 10. Urine Tungsten (Panel A) and Uranium (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose); DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



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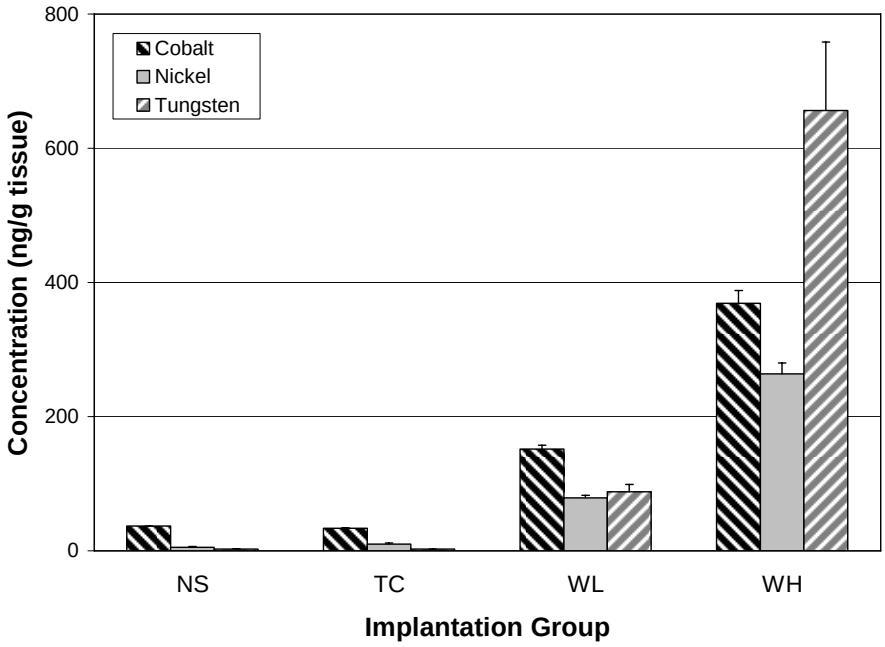


Figure 11. Kidney Metal (Co, Ni, W) Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

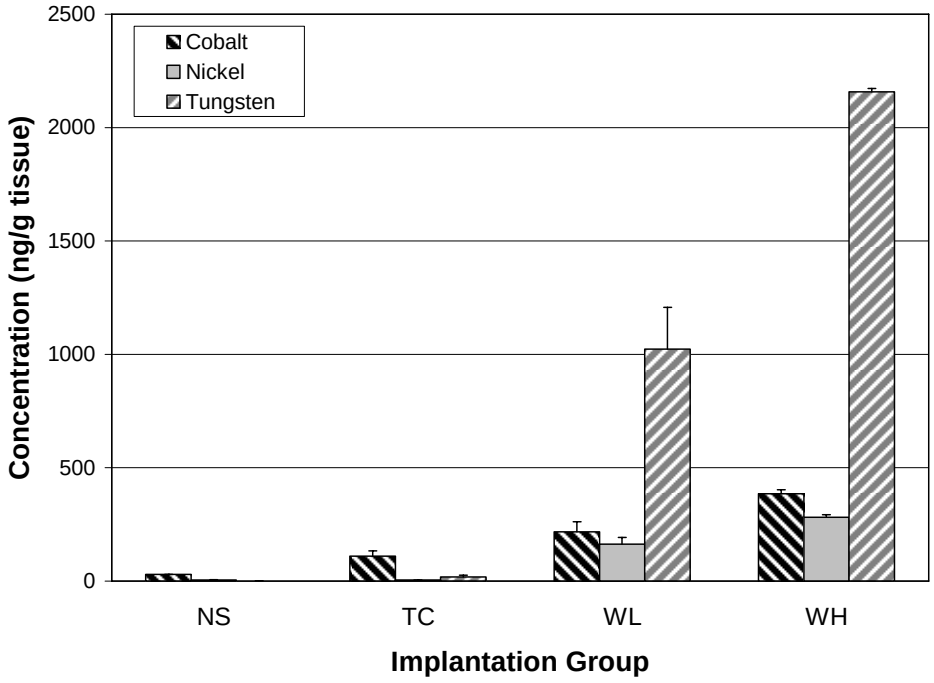
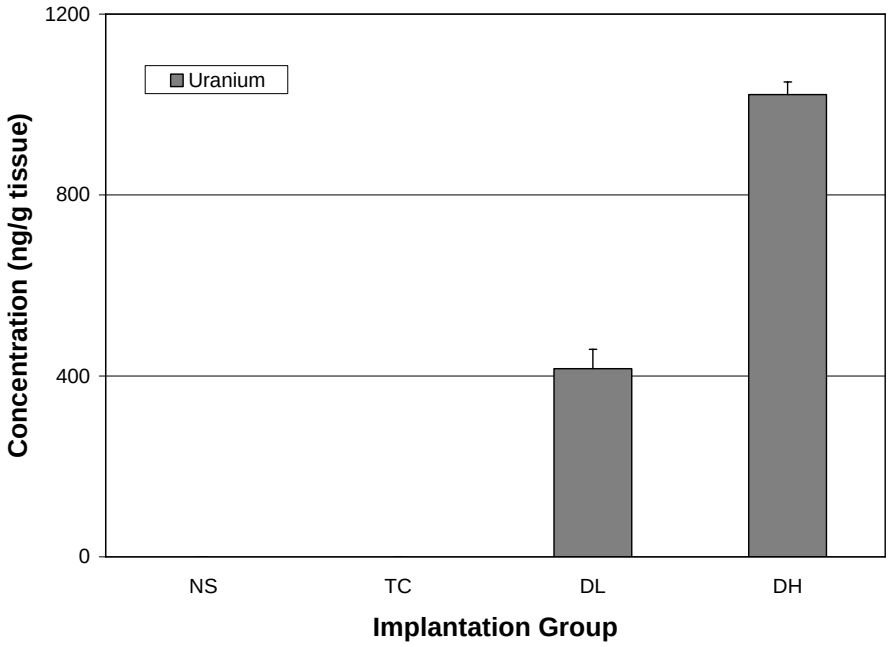


Figure 12. Kidney Metal (Co, Ni, W) Concentrations: 6 Month Group. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



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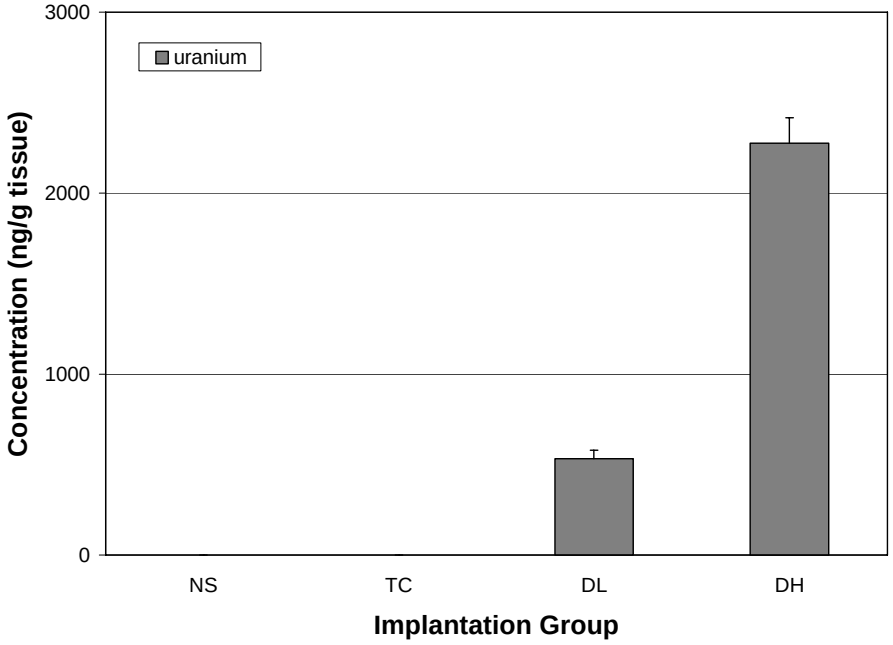
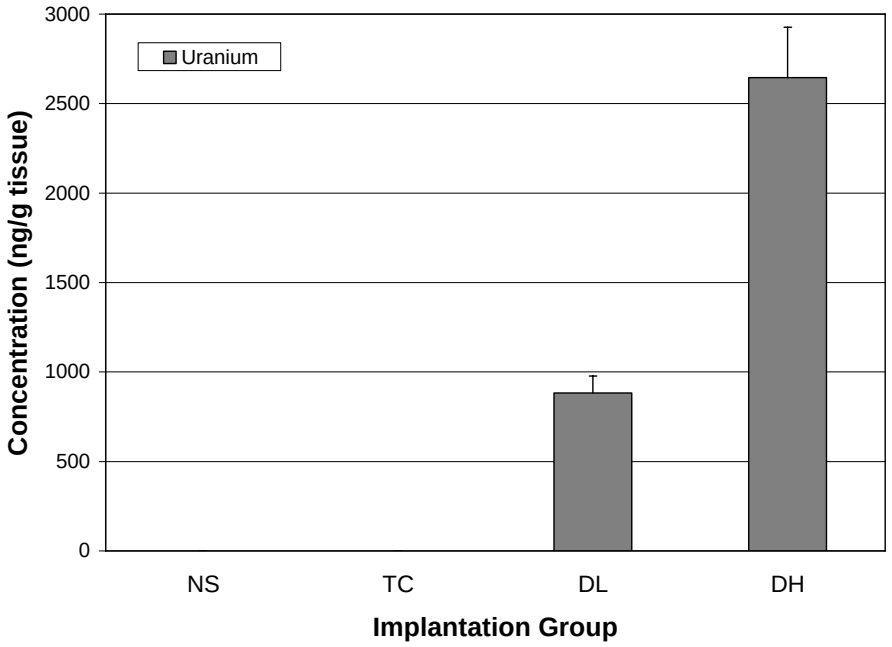


Figure 13. Kidney Uranium Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



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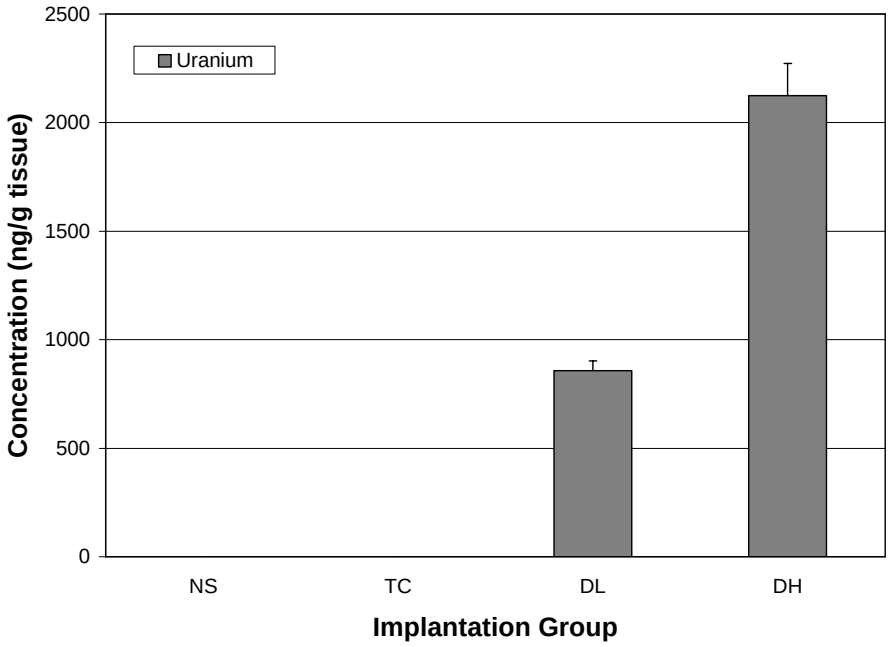


Figure 14. Kidney Uranium Concentrations: 6 Month (Panel A) and 12 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

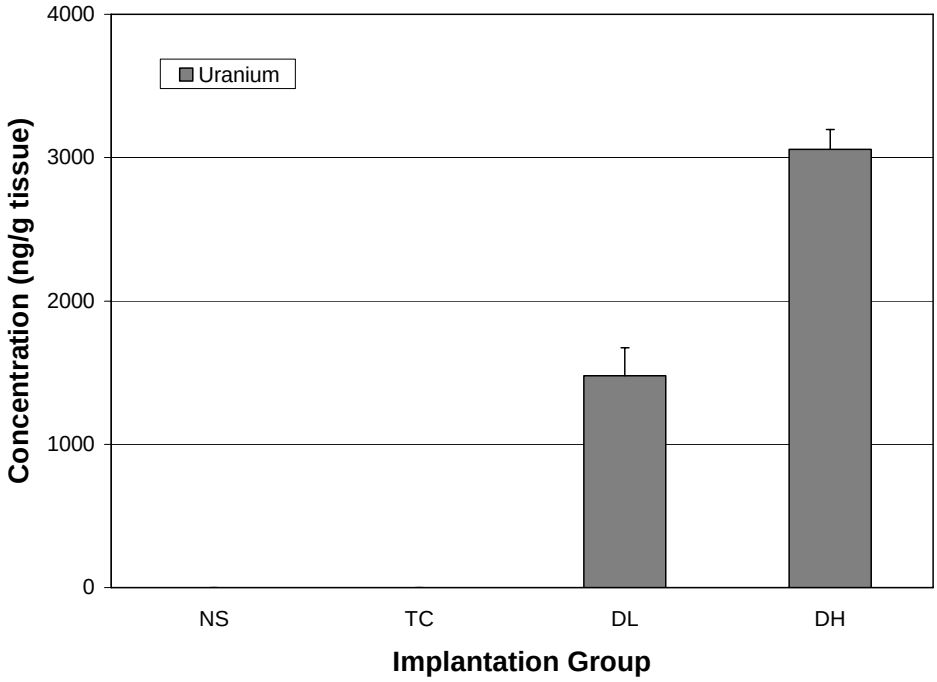
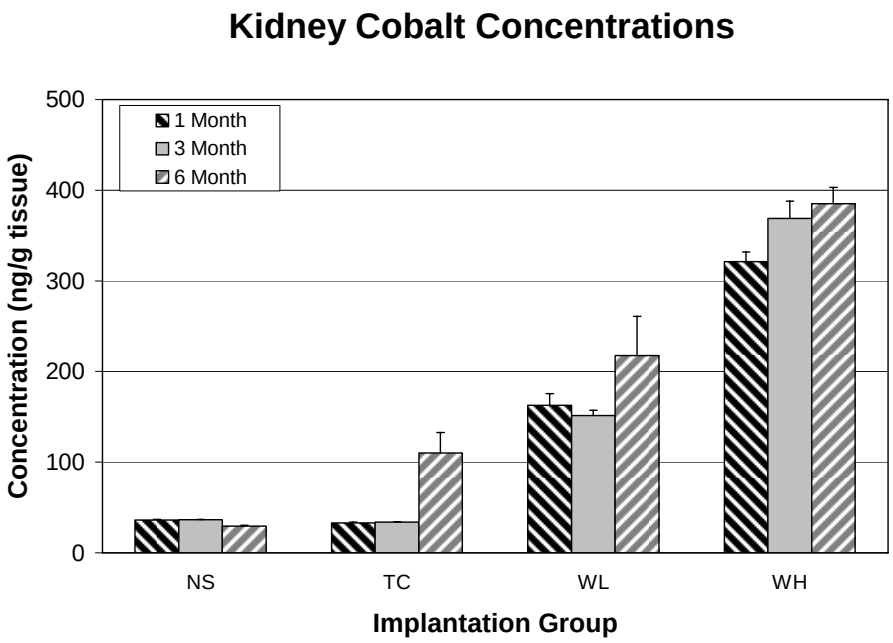


Figure 15. Kidney Uranium Concentrations: 18 Month Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

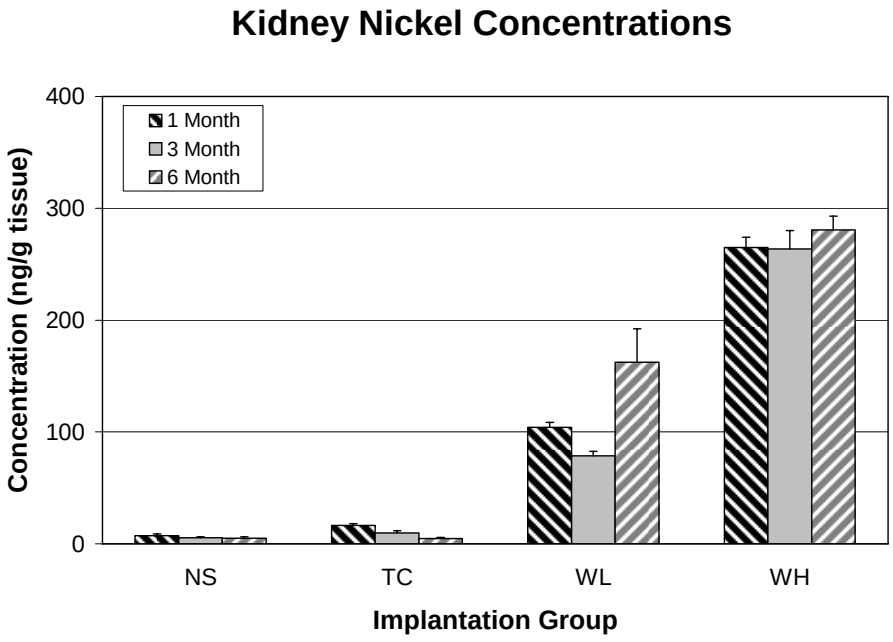
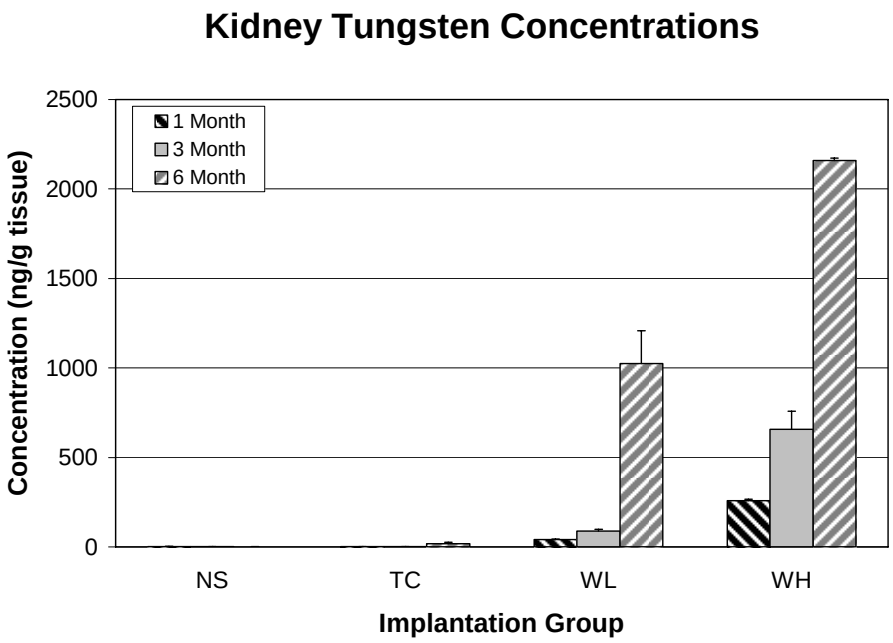


Figure 16. Kidney Cobalt (Panel A) and Nickel (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



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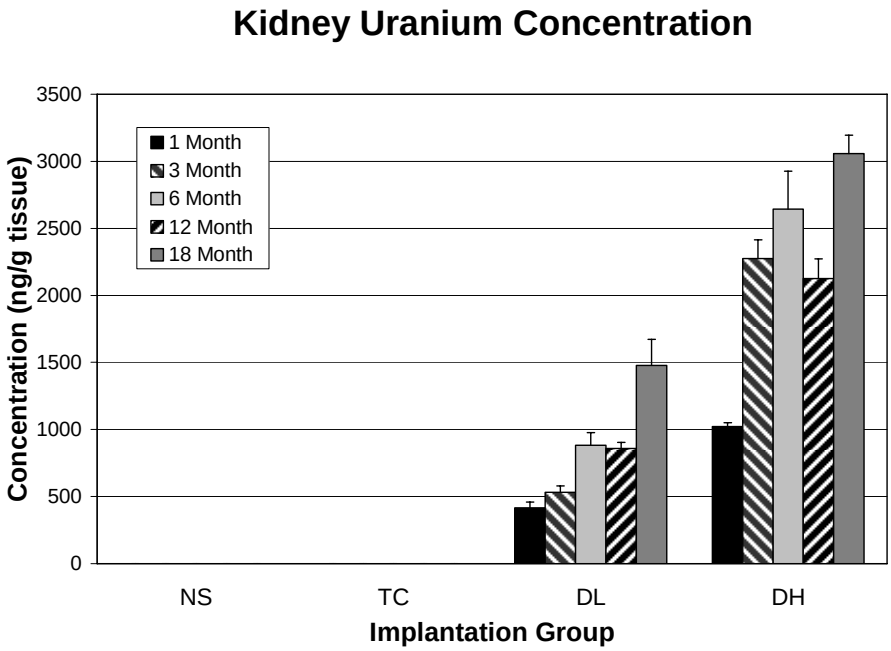
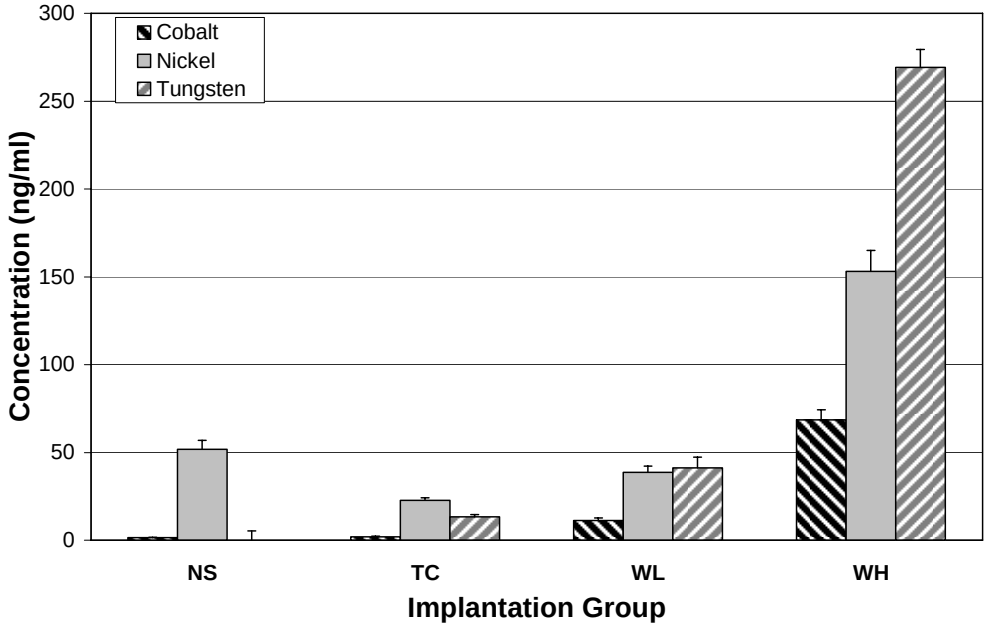


Figure 17. Kidney Tungsten (Panel A) and Uranium (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose); DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



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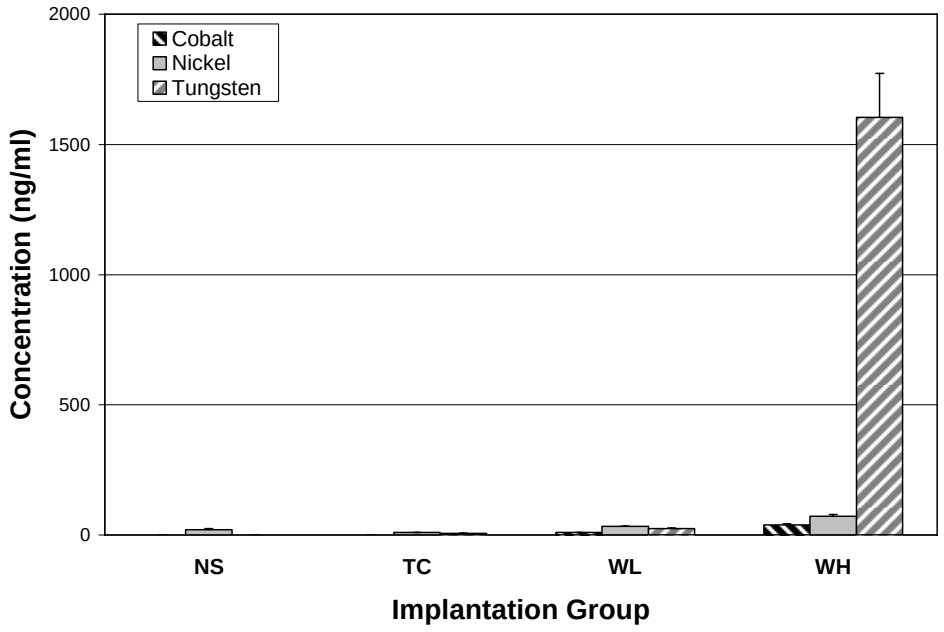


Figure 18. Serum Metal (Co, Ni, W) Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

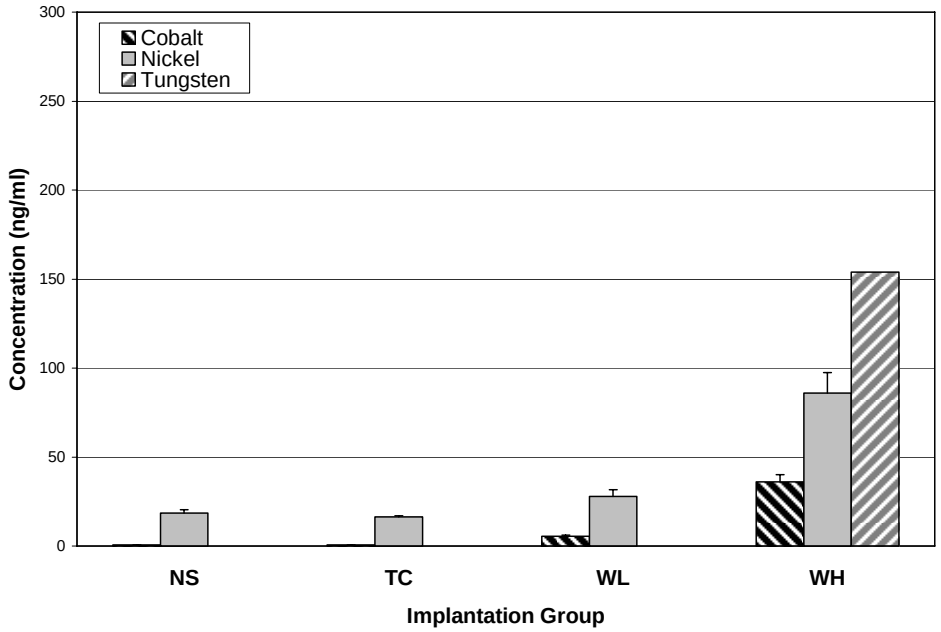
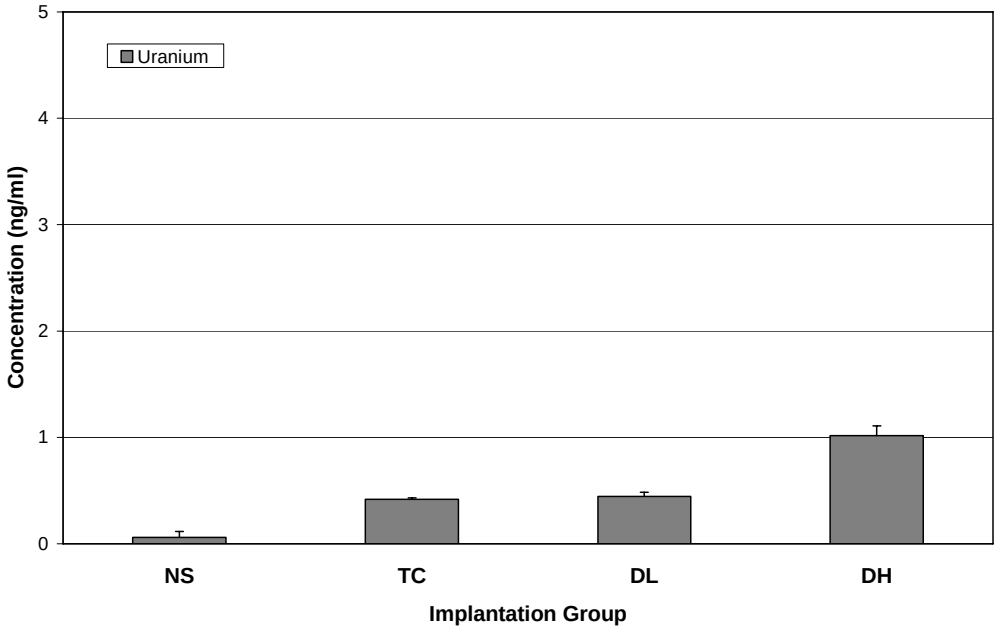


Figure 19. Serum Metal (Co, Ni, W) Concentrations: 6 Month Group. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



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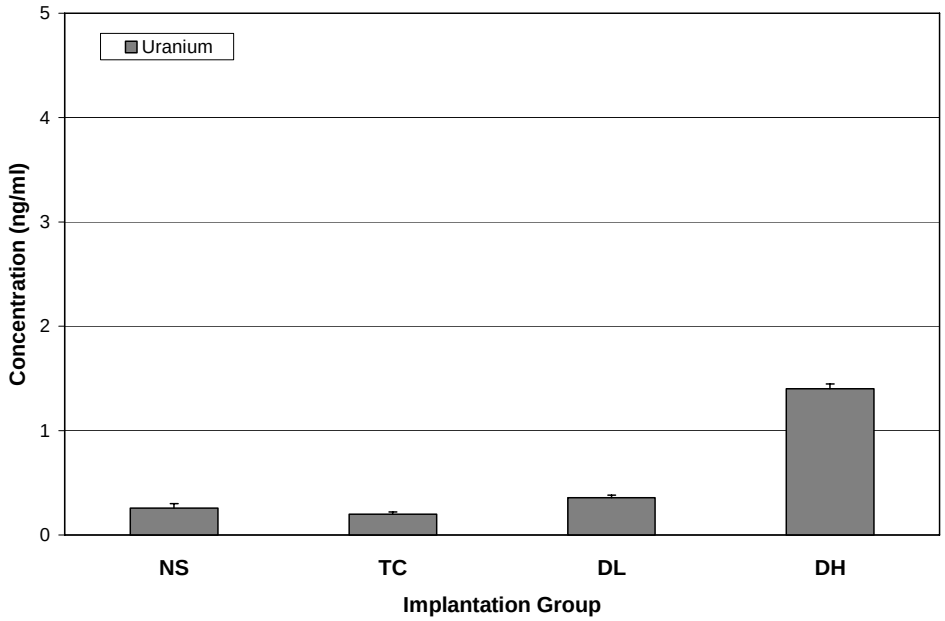
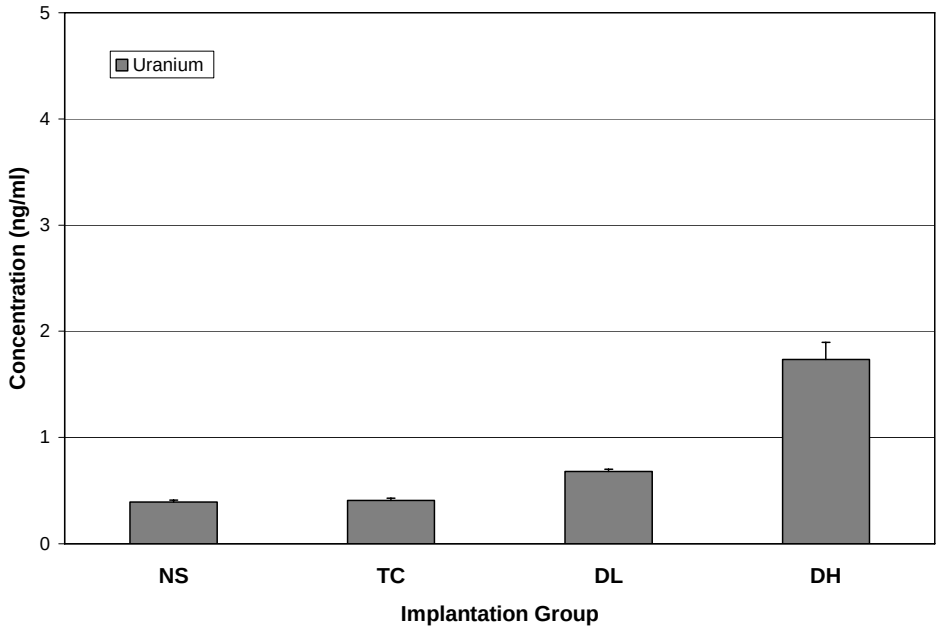


Figure 20. Serum Uranium Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



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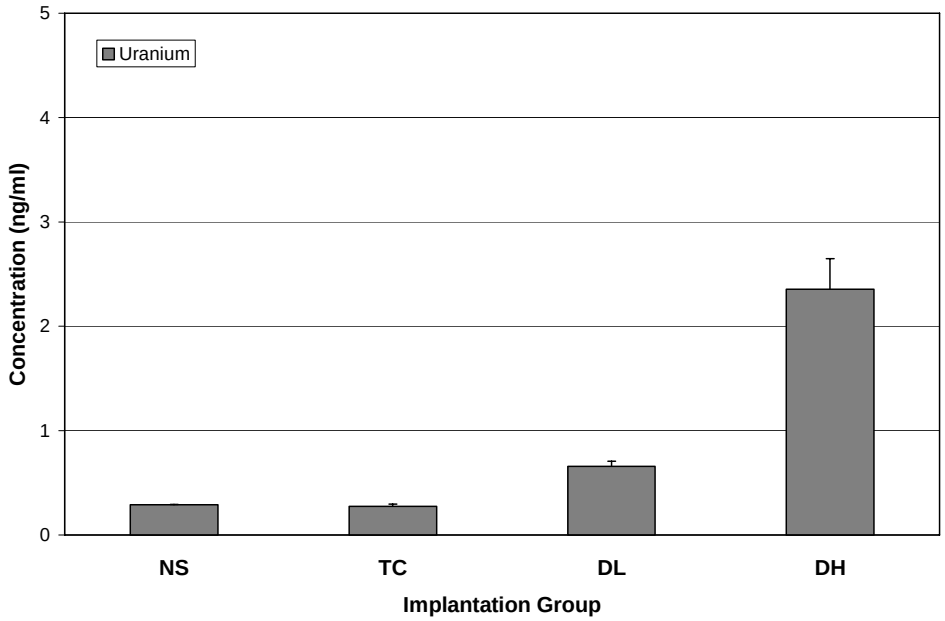


Figure 21. Serum Uranium Concentrations: 6 Month (Panel A) and 12 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

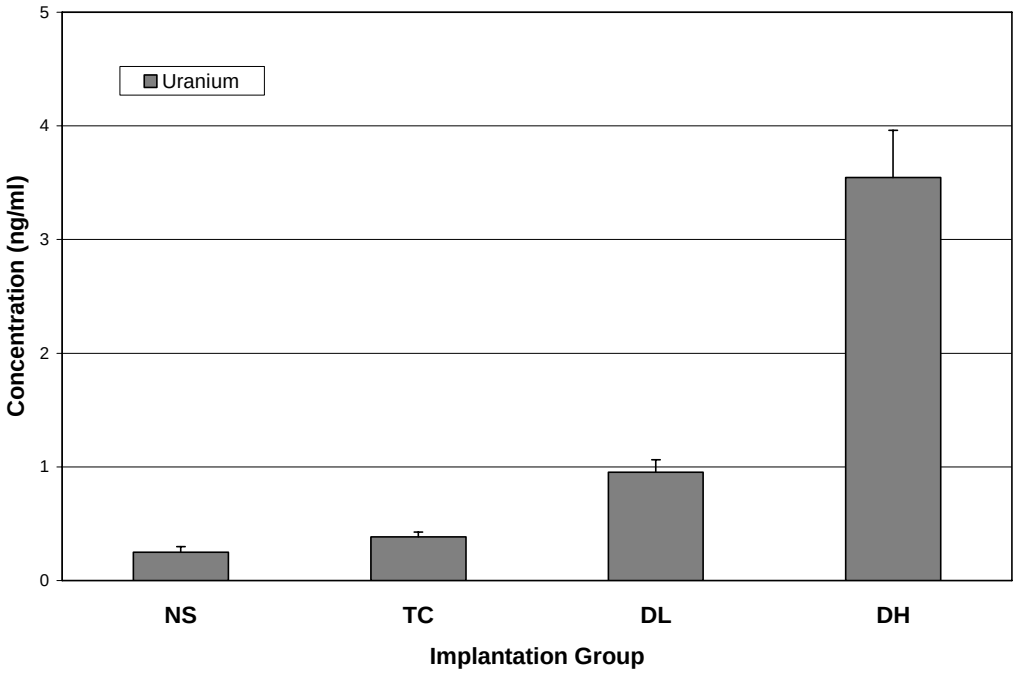
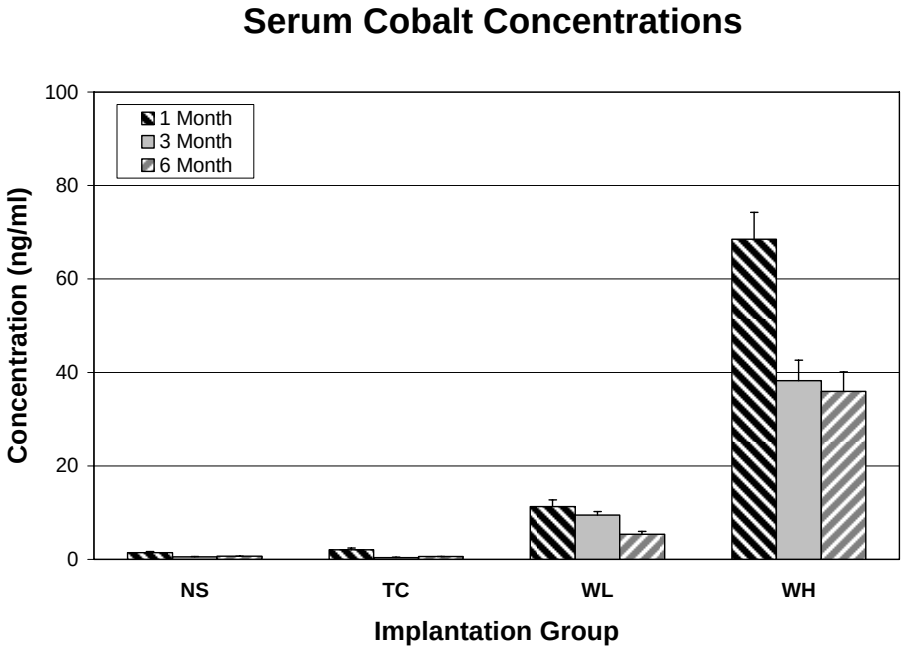


Figure 22. Serum Uranium Concentrations: 18 Month Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

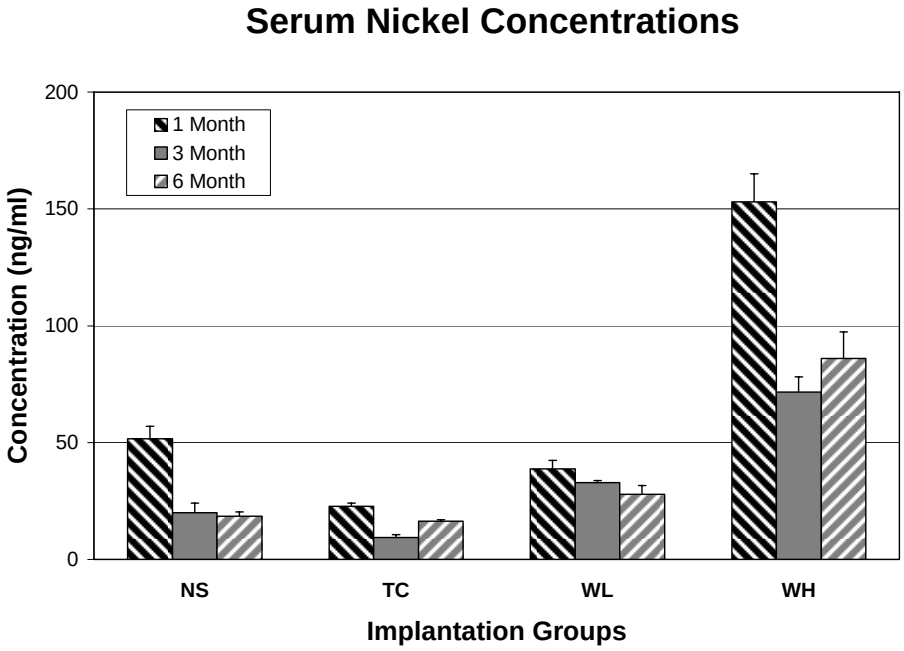
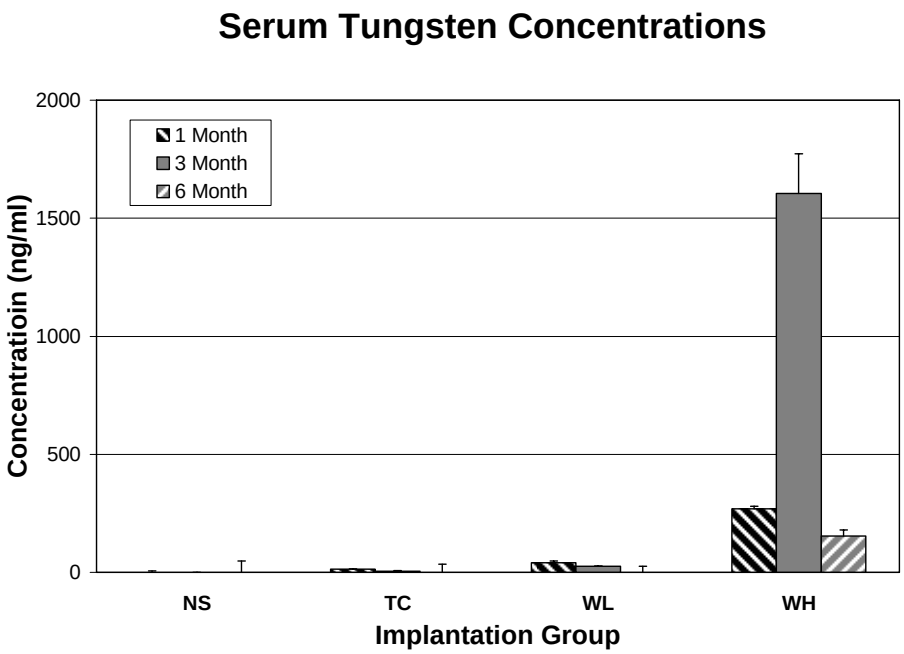


Figure 23. Serum Cobalt (Panel A) and Nickel (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



B

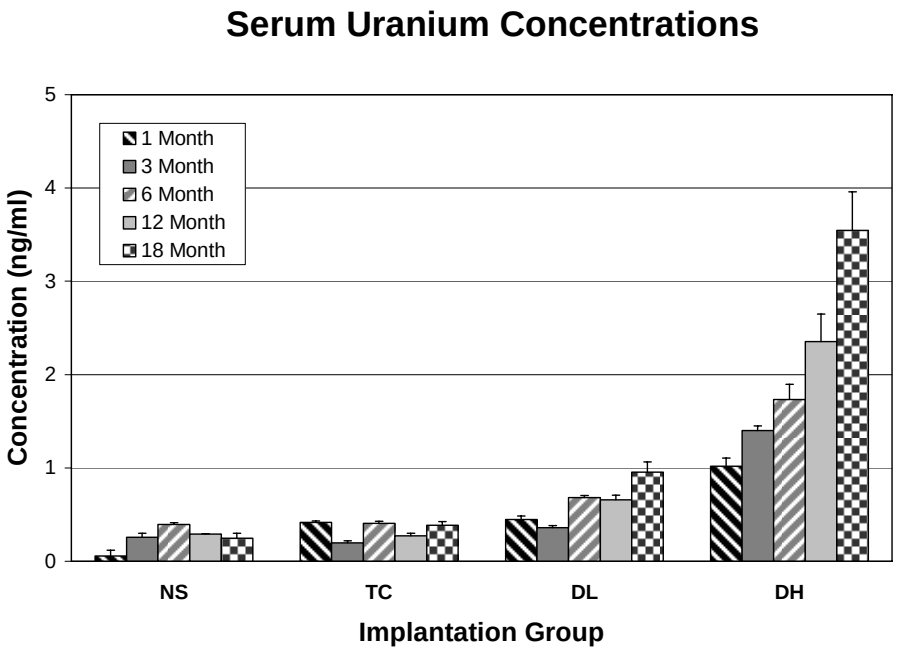
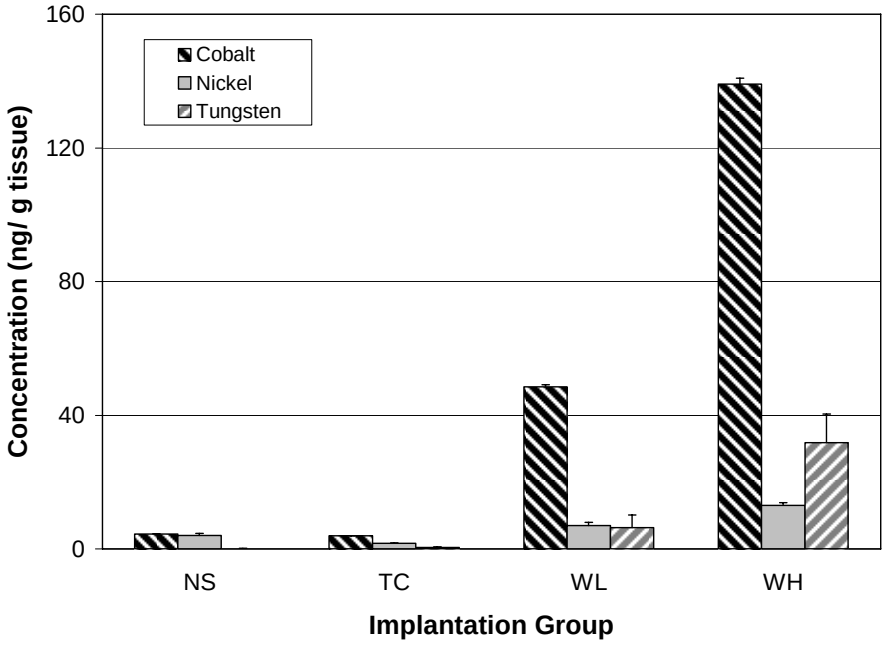


Figure 24. Serum Cobalt (Panel A) and Nickel (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose); DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

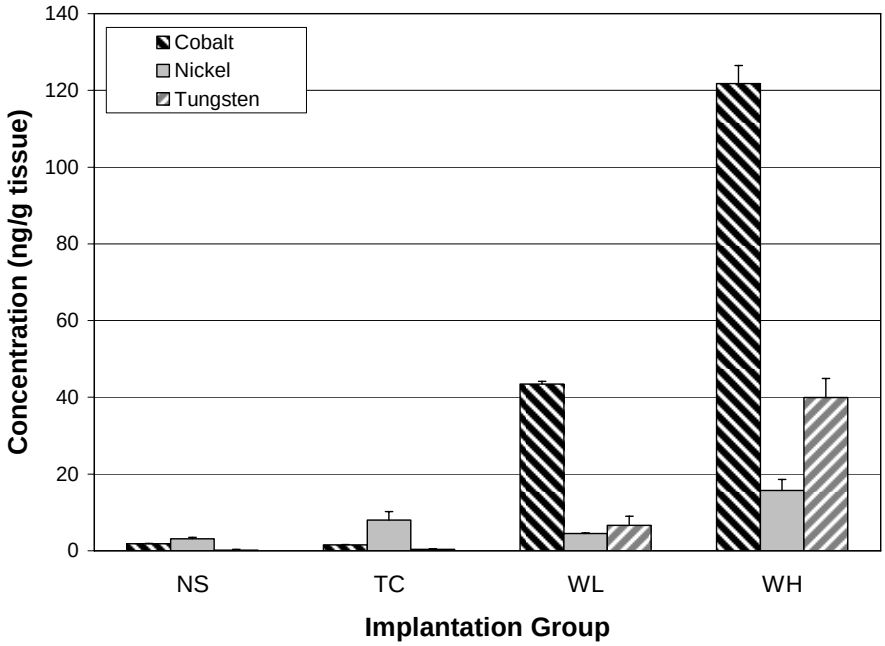


Figure 25. Liver Metal (Co, Ni, W) Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

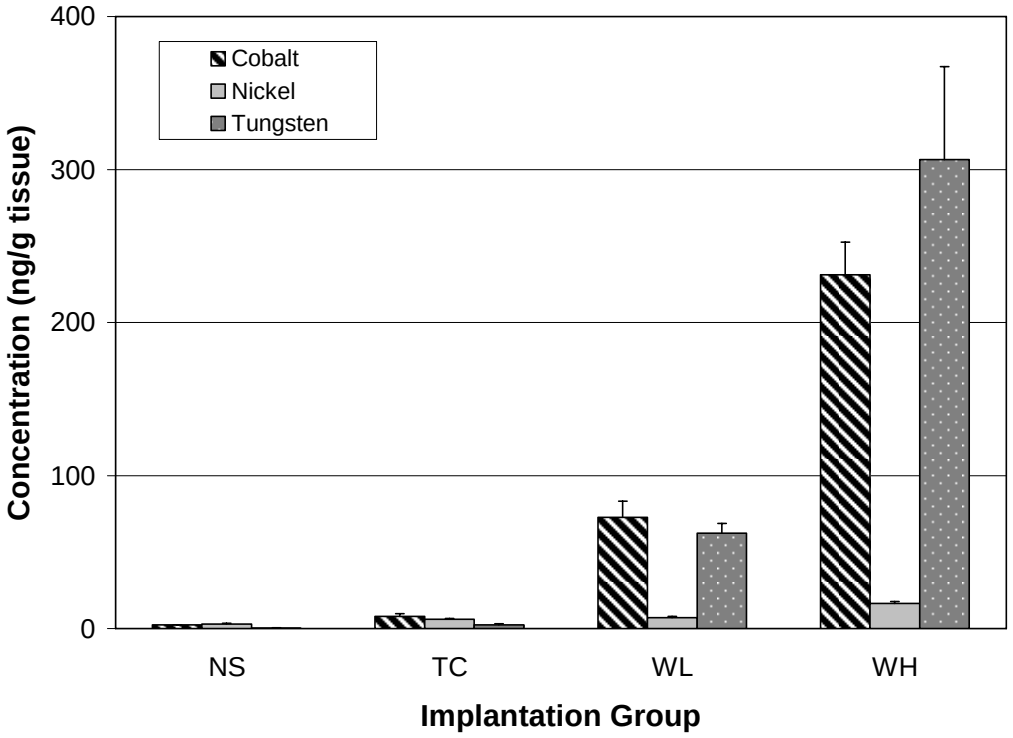
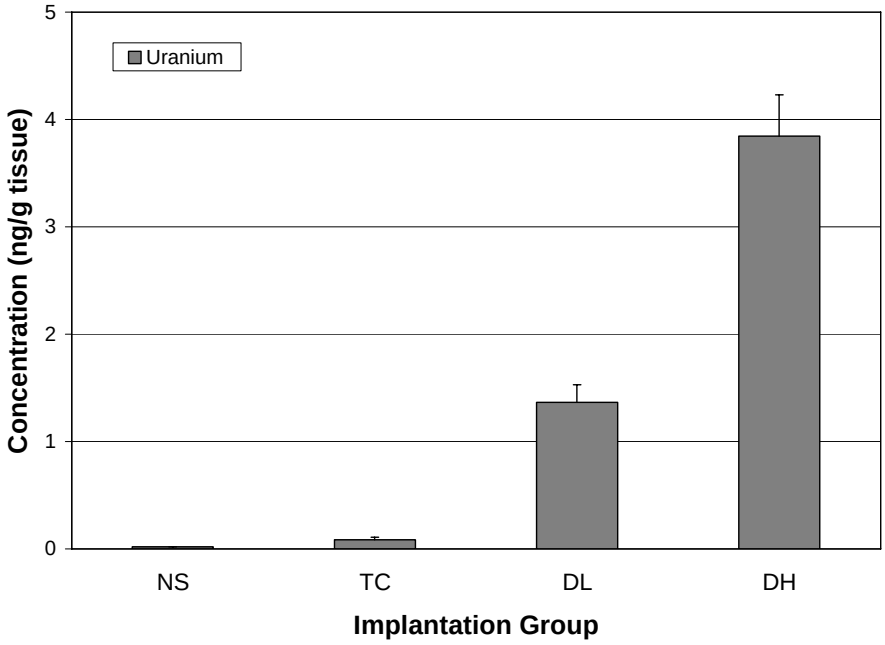


Figure 26. Liver Metal (Co, Ni, W) Concentrations: 6 Month Group. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



B

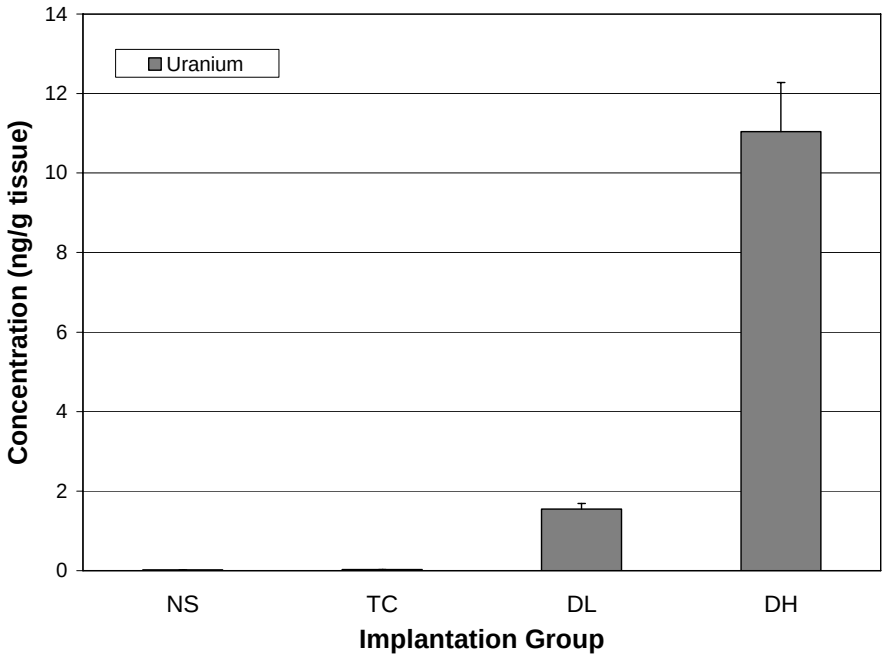
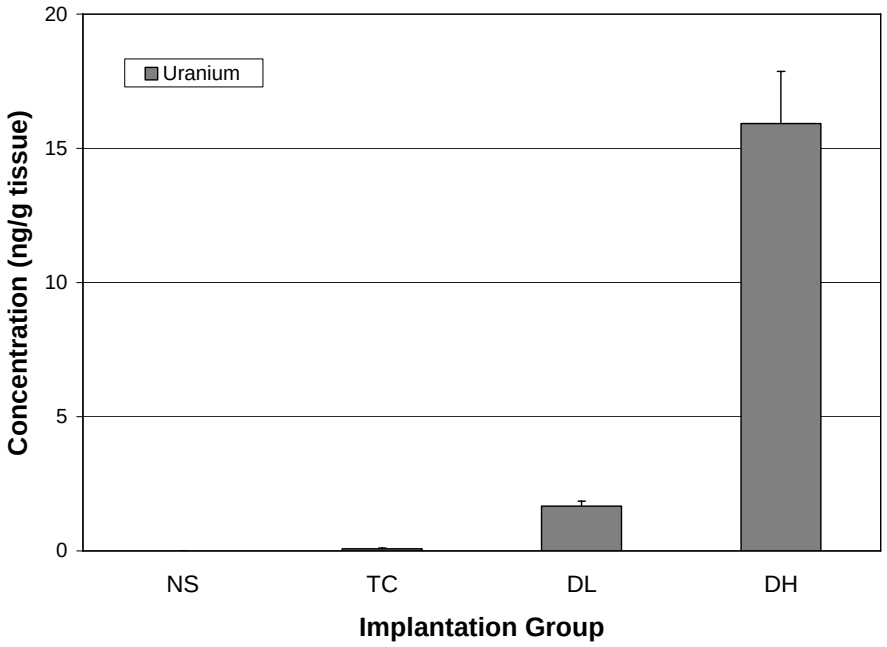


Figure 27. Liver Uranium Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

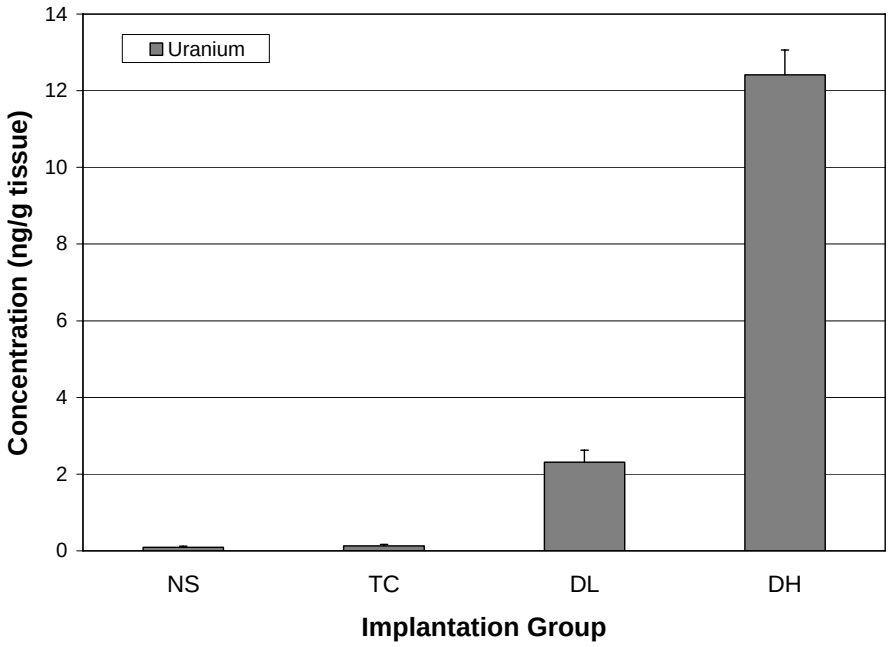


Figure 28. Liver Uranium Concentrations: 6 Month (Panel A) and 12 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH-depleted uranium (high dose).

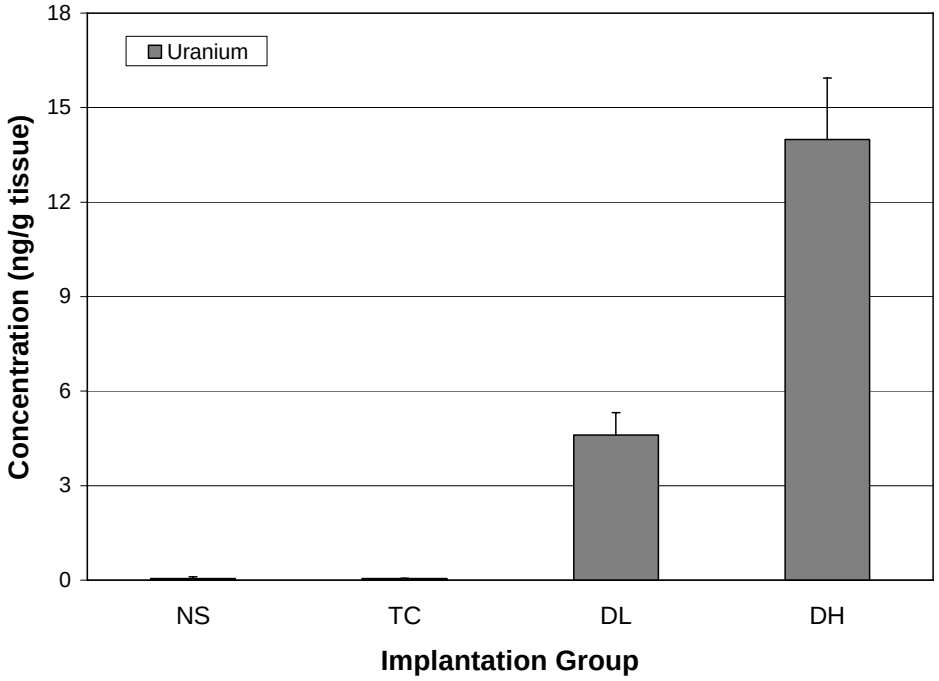
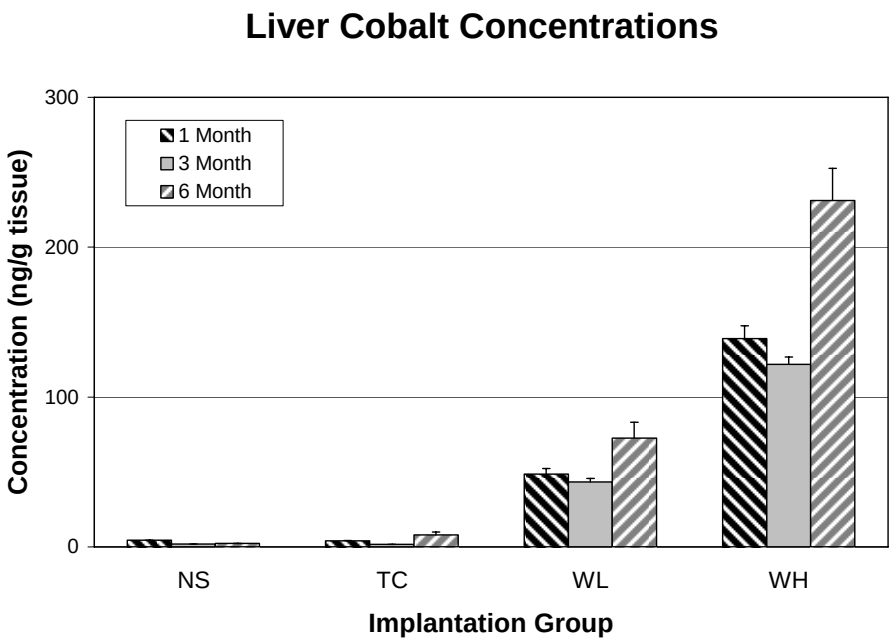


Figure 29. Liver Uranium Concentrations: 18 Month Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

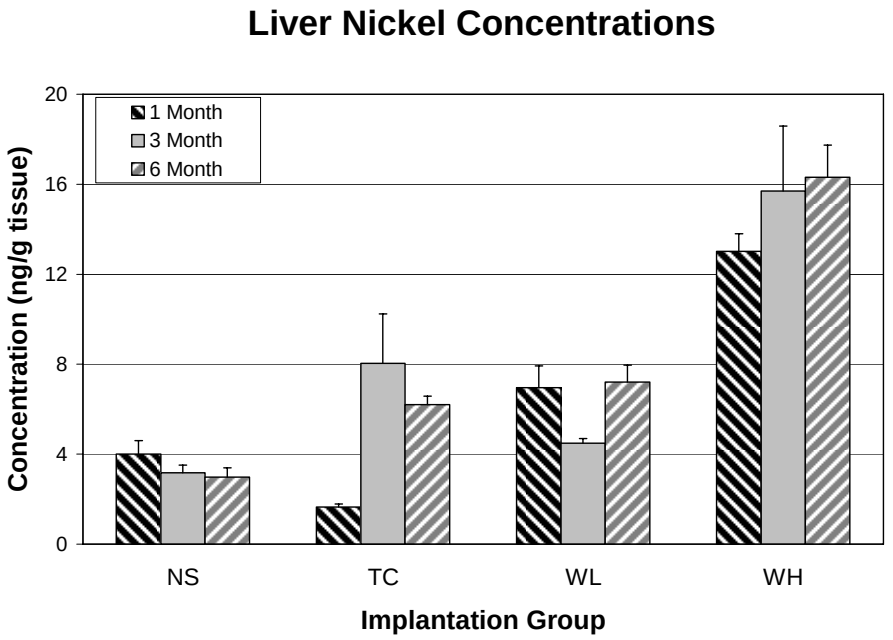
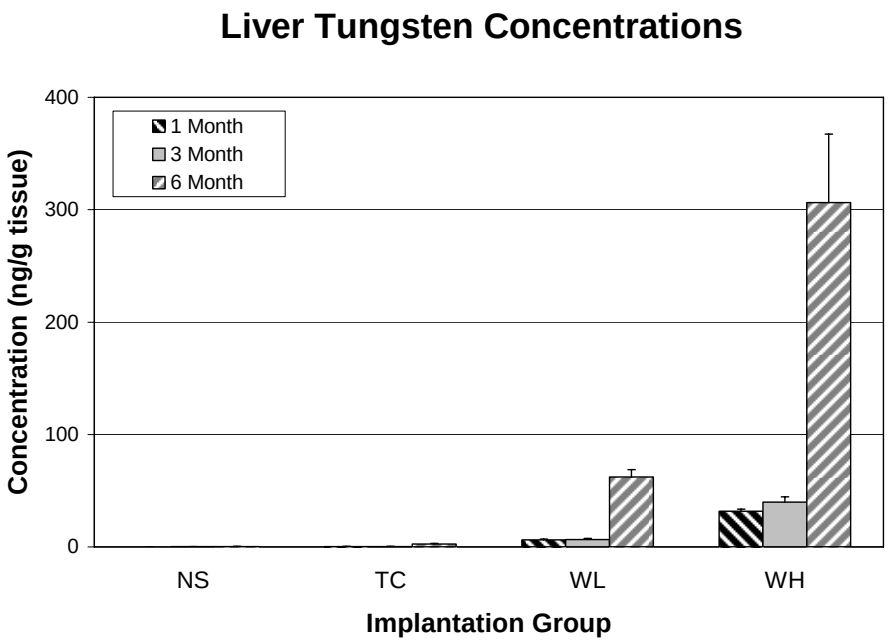


Figure 30. Liver Cobalt (Panel A) and Nickel (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



B

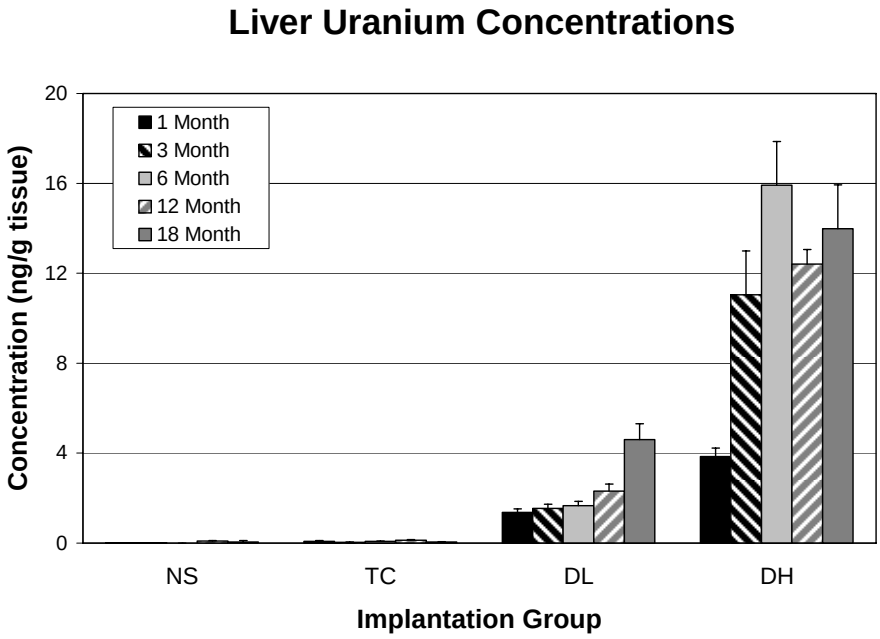
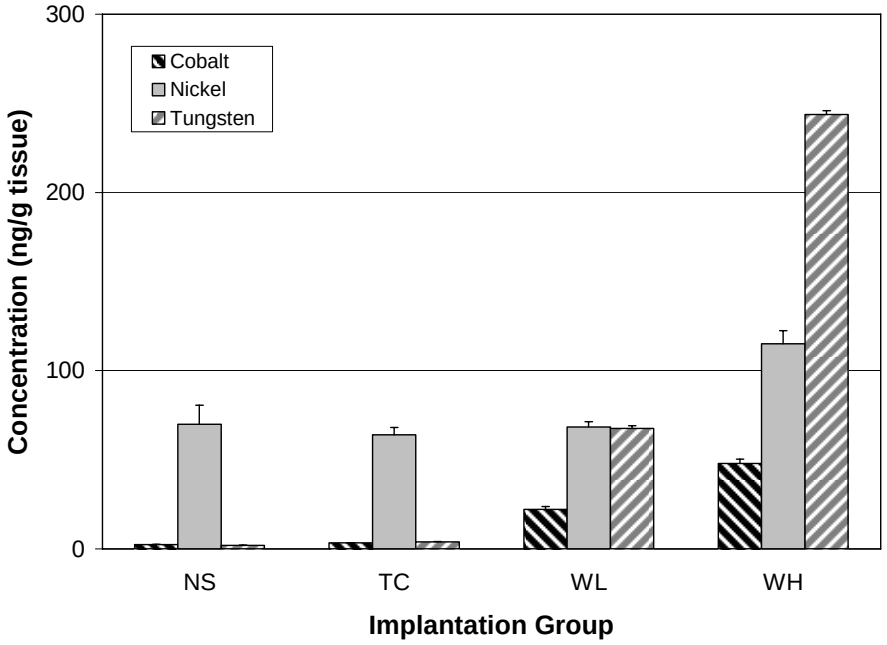


Figure 31. Liver Tungsten (Panel A) and Uranium (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose); DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

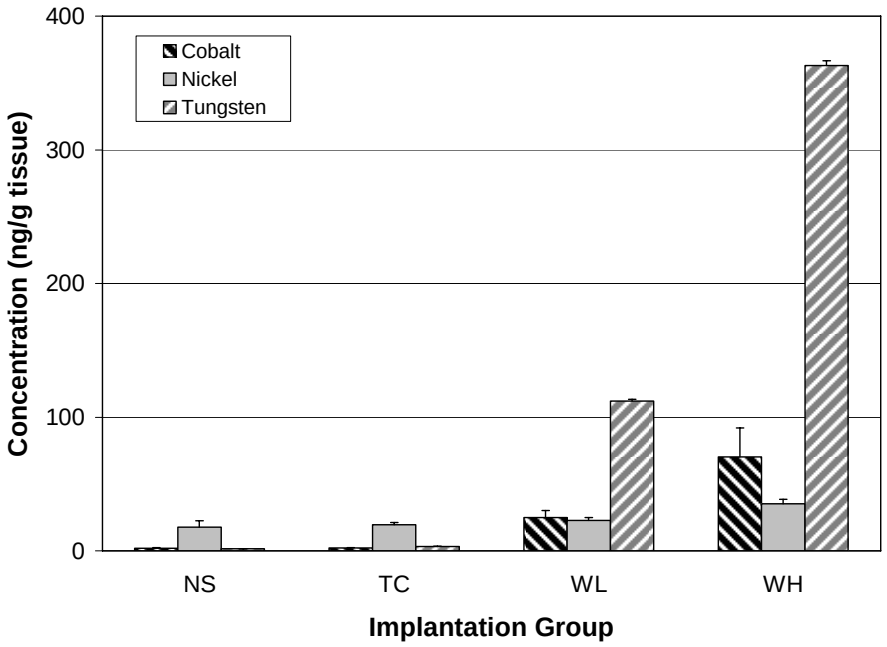


Figure 32. Spleen Metal (Co, Ni, W) Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

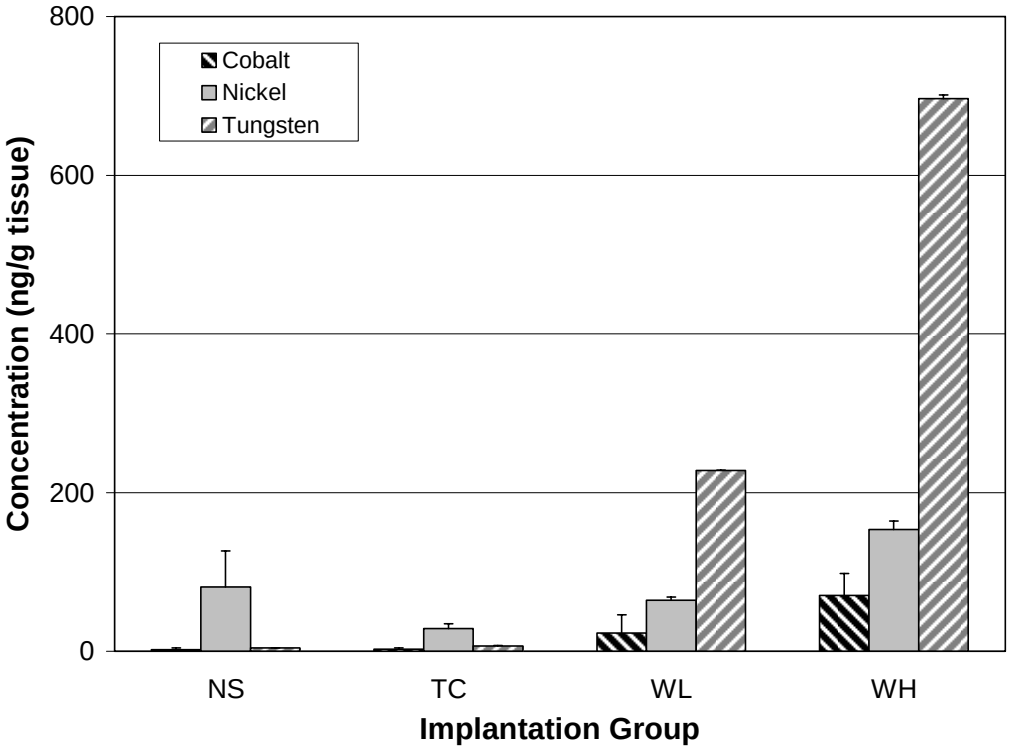
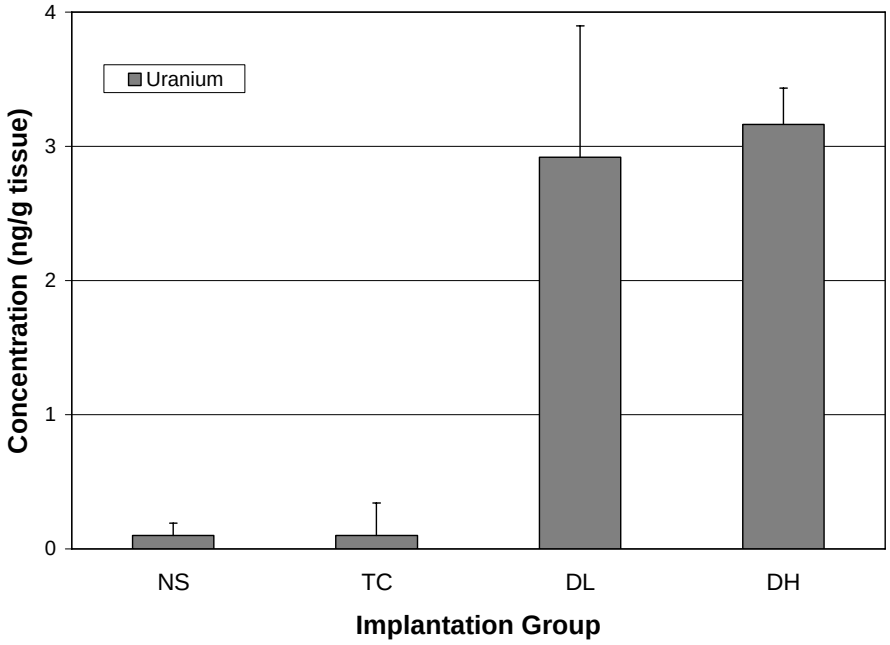


Figure 33. Spleen Metal (Co, Ni, W) Concentrations: 6 Month Group. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



B

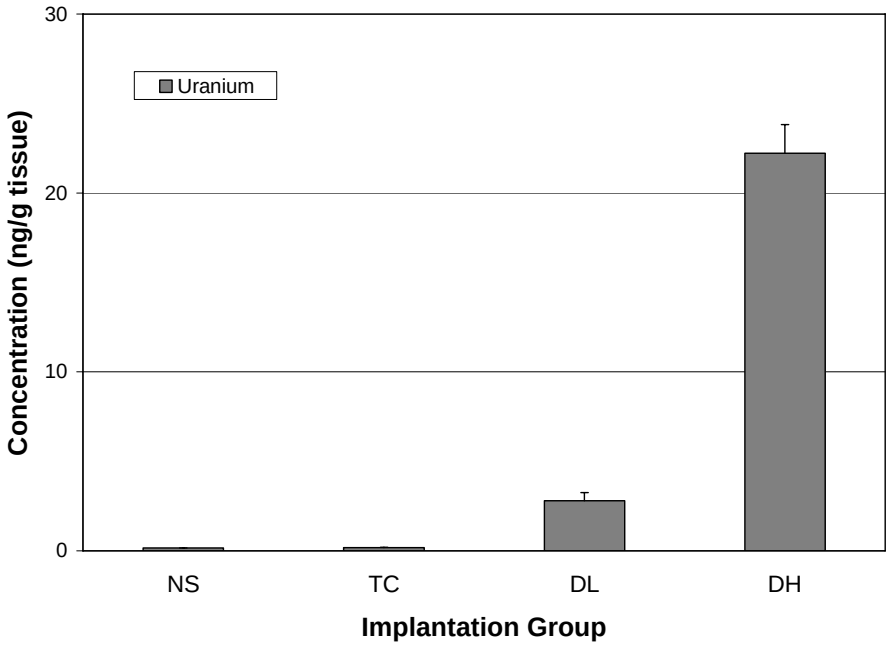
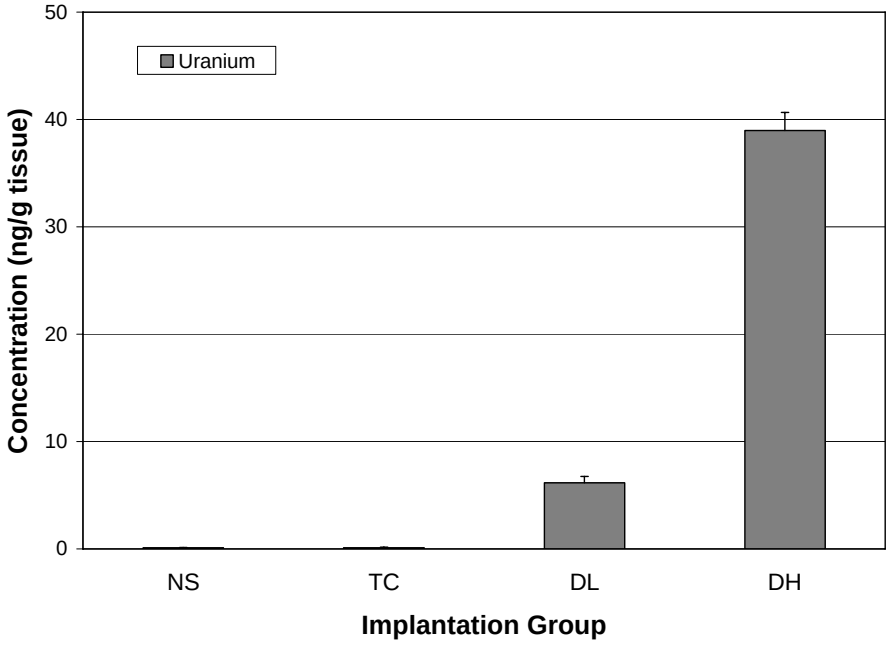


Figure 34. Spleen Uranium Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

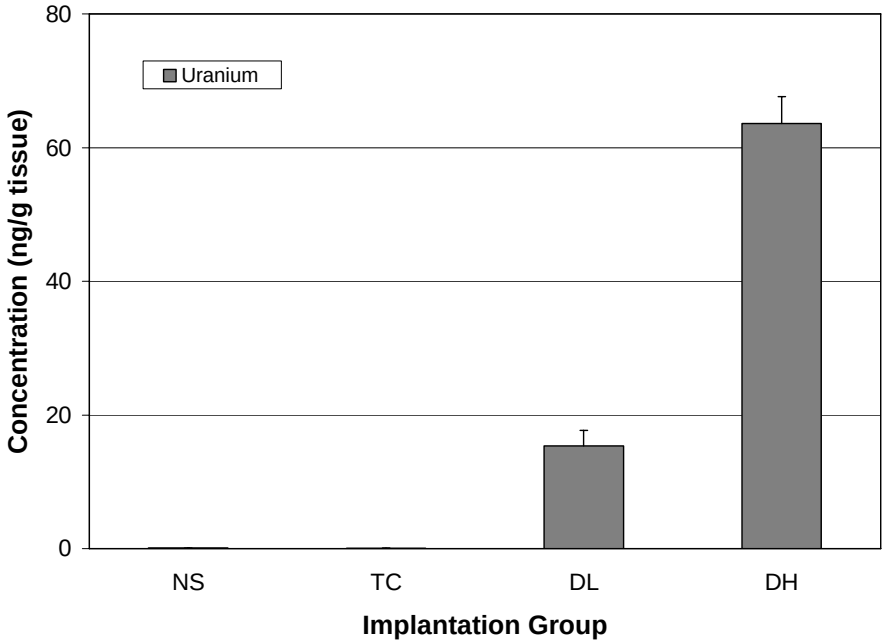


Figure 35. Spleen Uranium Concentrations: 6 Month (Panel A) and 12 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

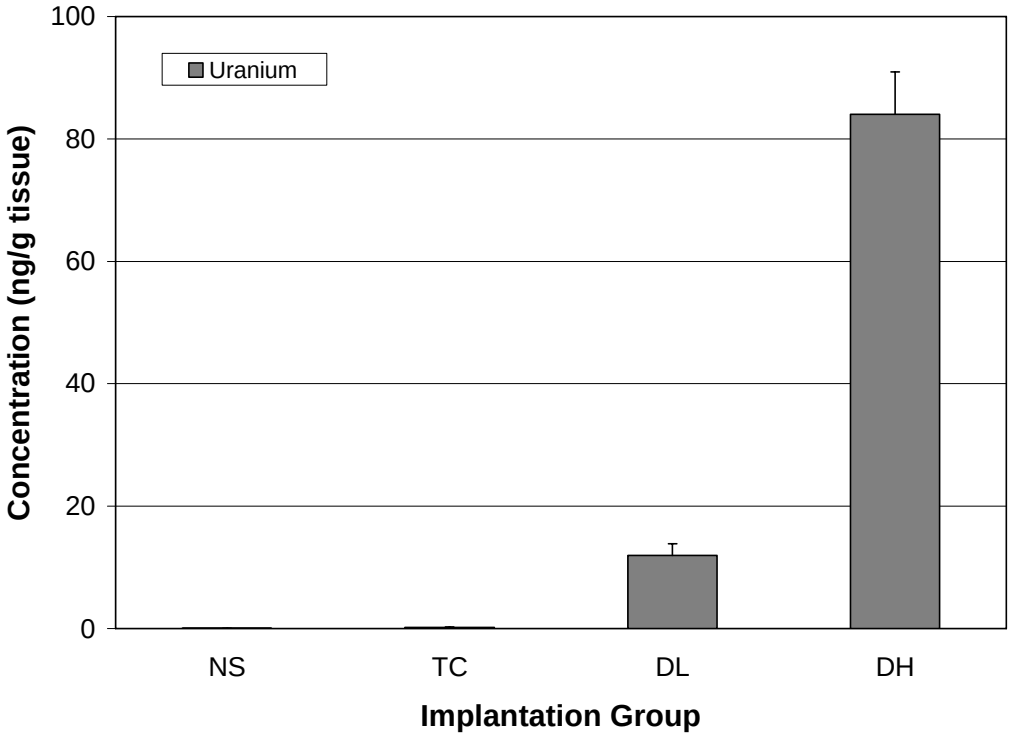
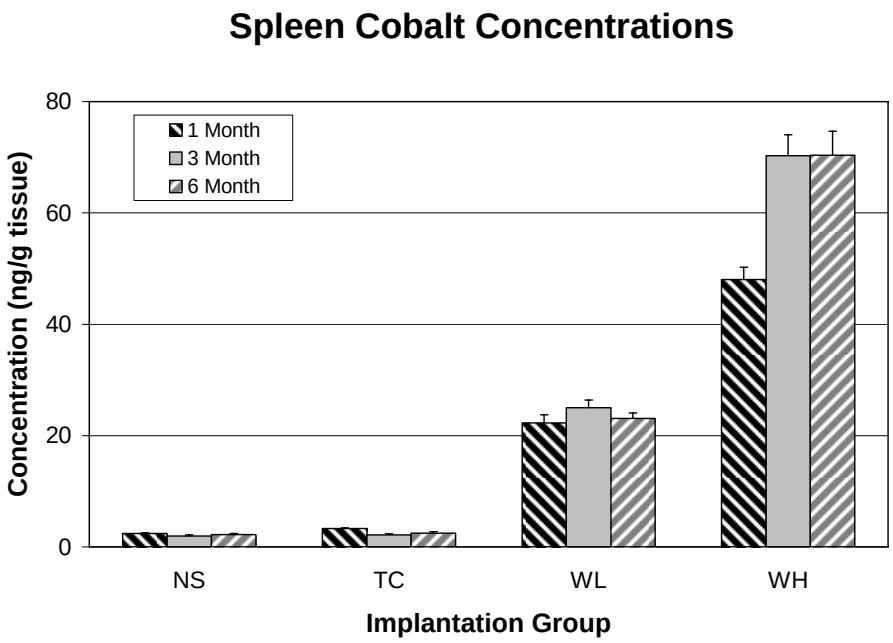


Figure 36. Spleen Uranium Concentrations: 18 Month Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

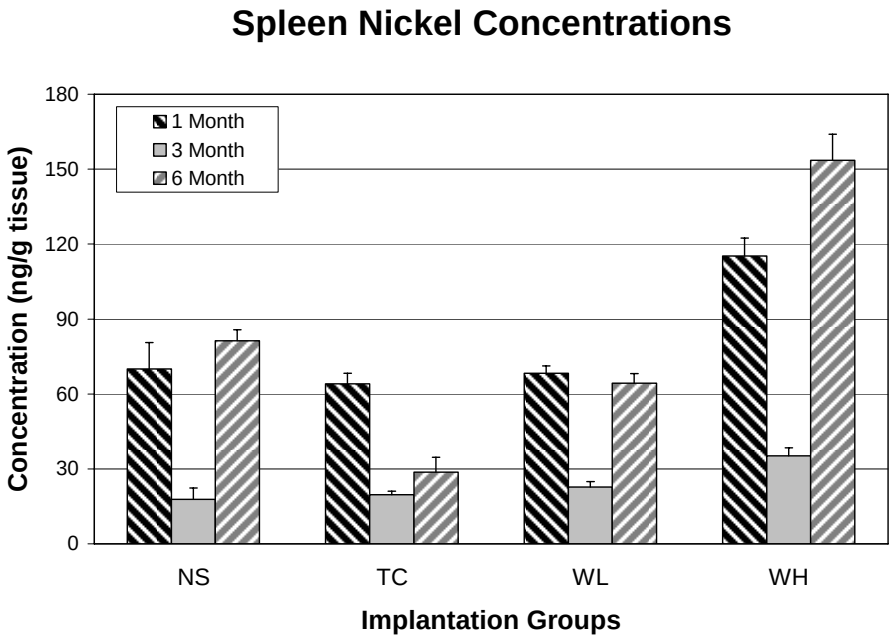
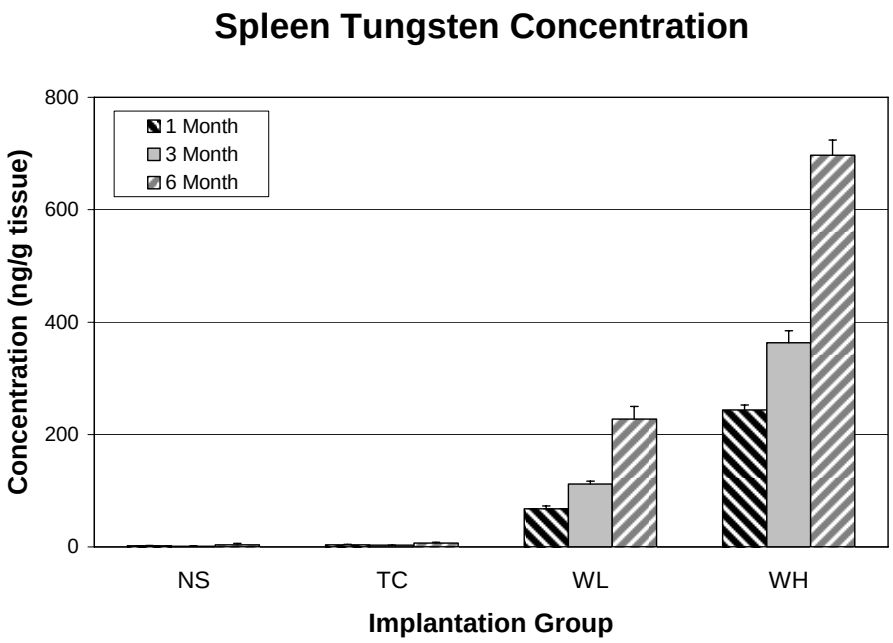


Figure 37. Spleen Cobalt (Panel A) and Nickel (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



B

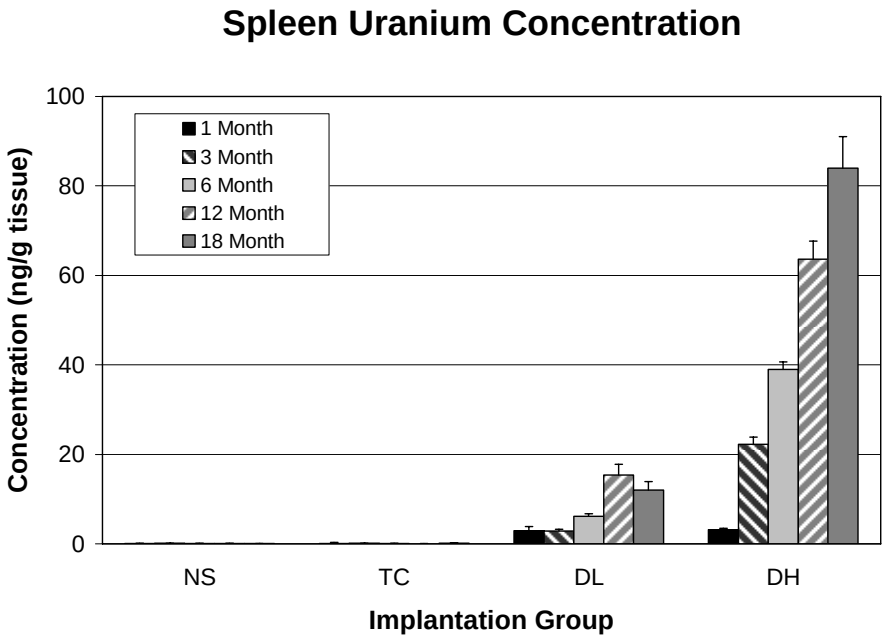
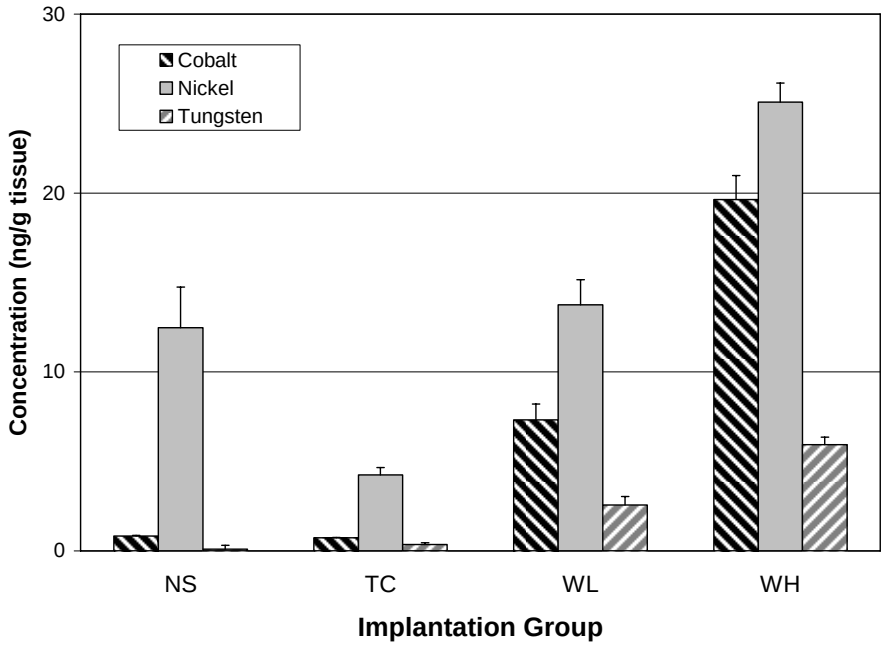


Figure 38. Kidney Cobalt (Panel A) and Nickel (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose); DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

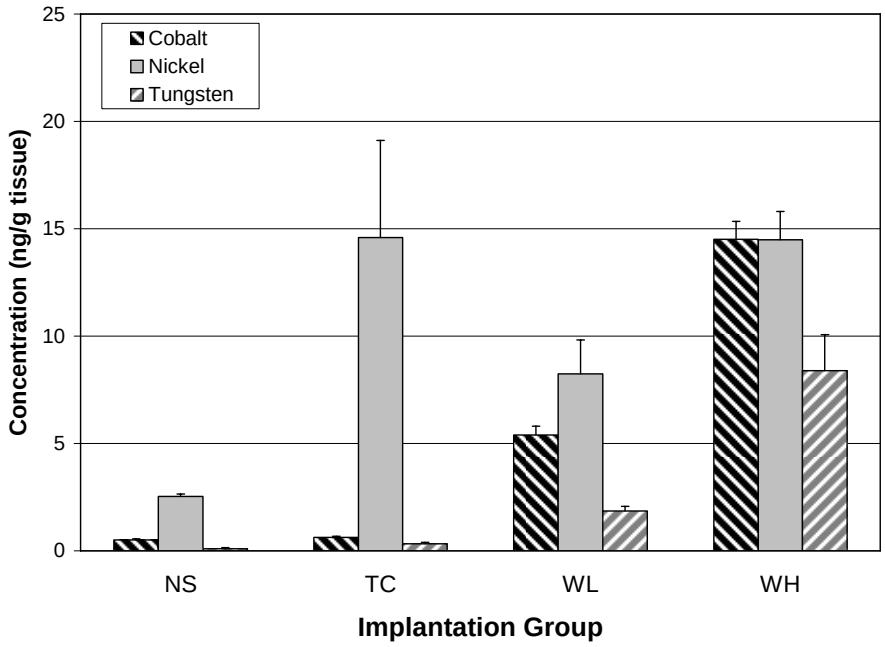


Figure 39. Muscle Metal (Co, Ni, W) Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

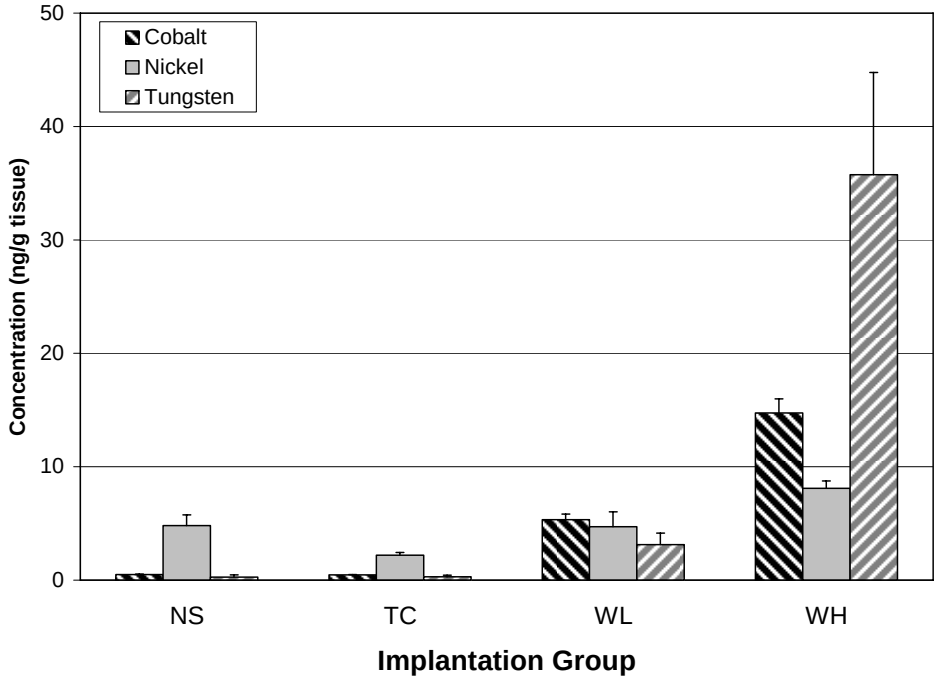
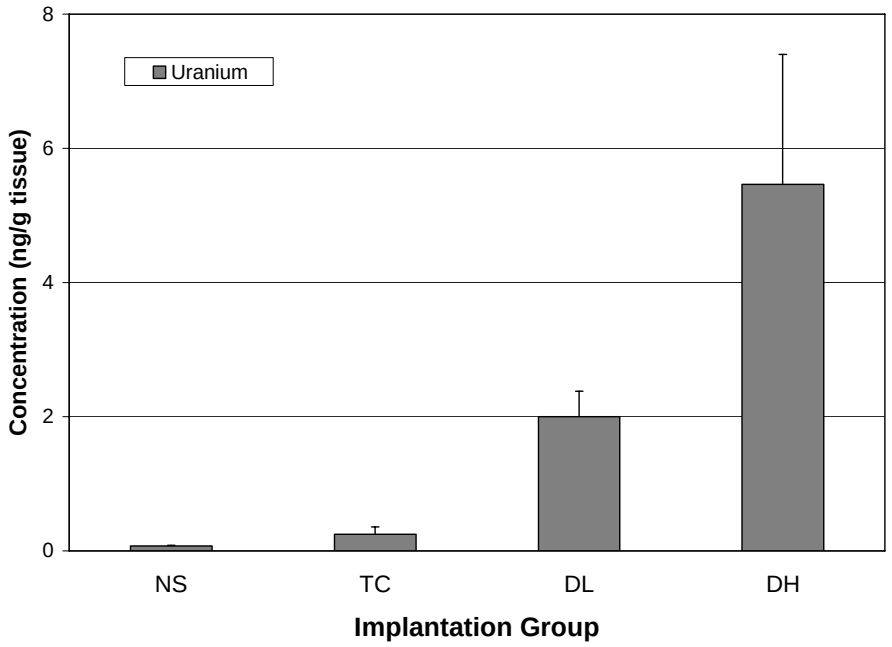


Figure 40. Muscle Metal (Co, Ni, W) Concentrations: 6 Month Group. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).

A



B

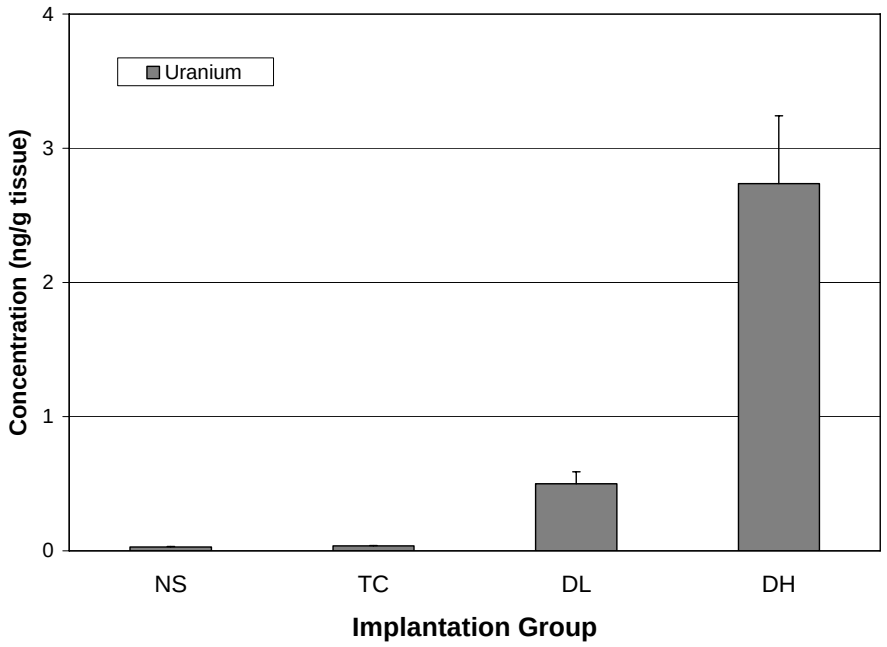
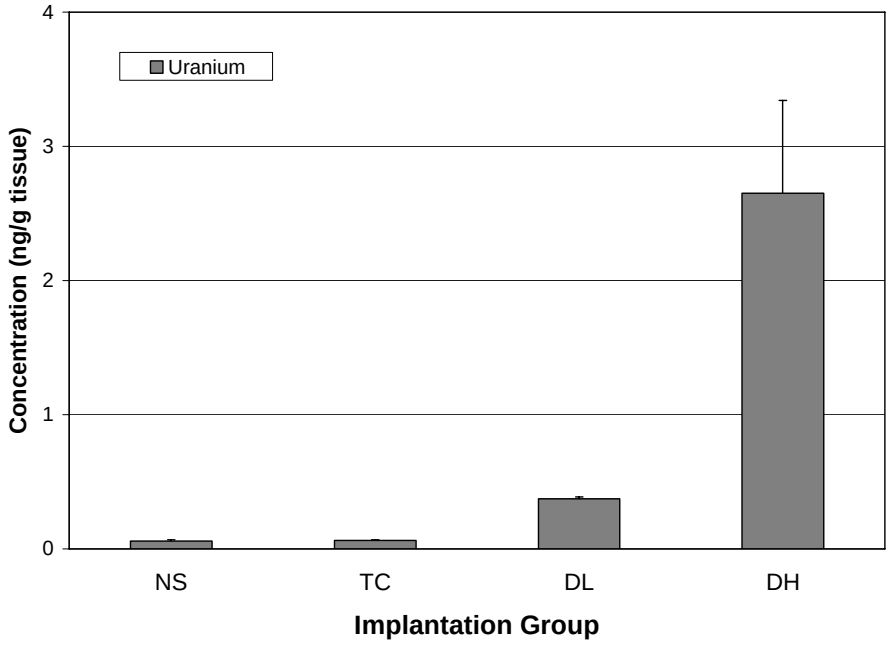


Figure 41. Muscle Uranium Concentrations: 1 Month (Panel A) and 3 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

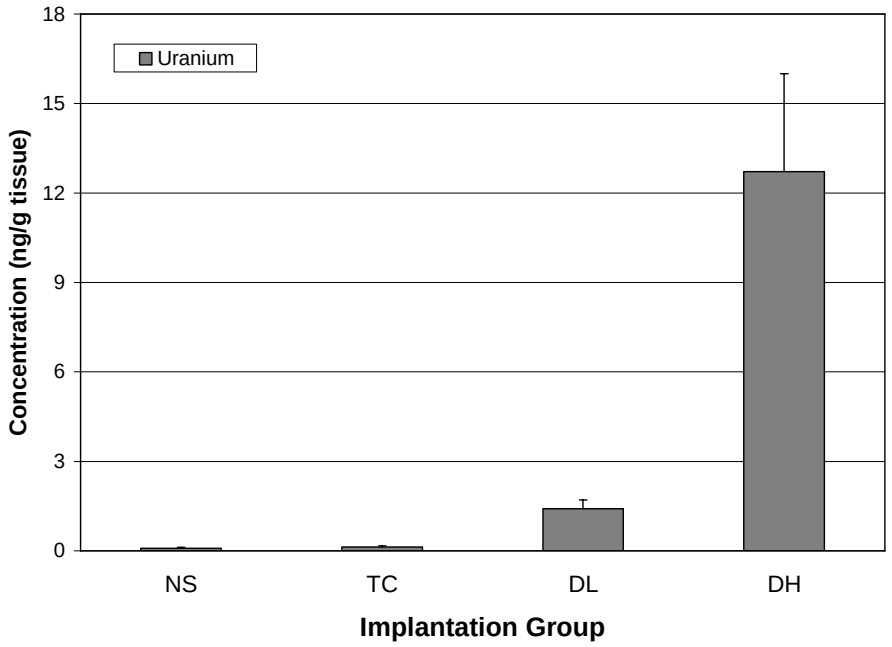


Figure 42. Muscle Uranium Concentrations: 6 Month (Panel A) and 12 Month (Panel B) Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

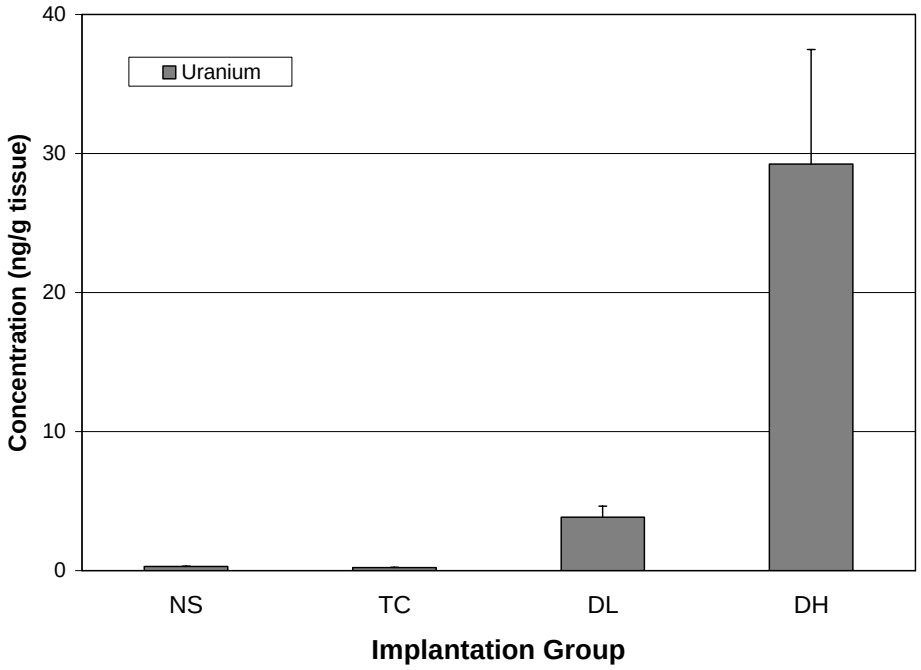
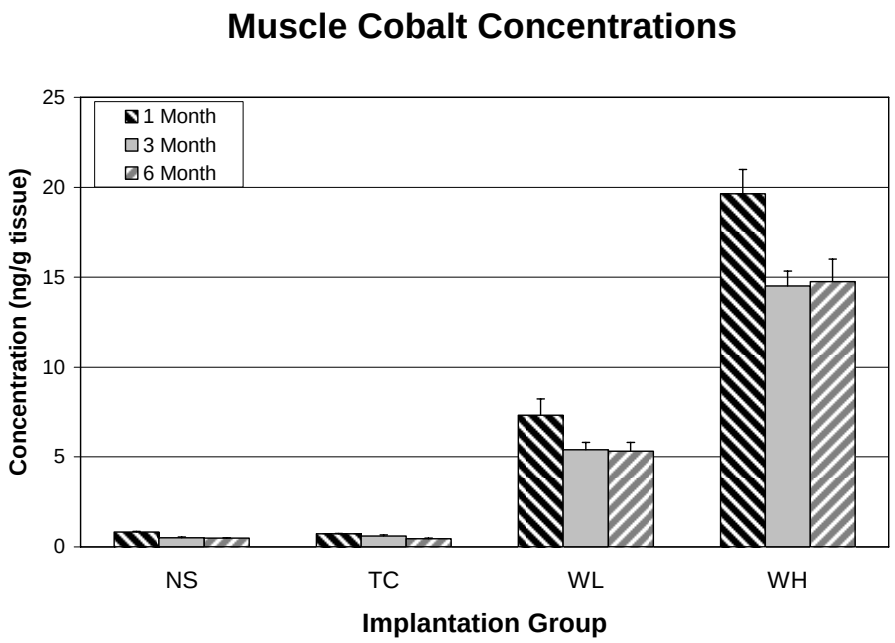


Figure 43. Muscle Uranium Concentrations: 18 Month Groups. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; DL-depleted uranium (low dose); DH- depleted uranium (high dose).

A



B

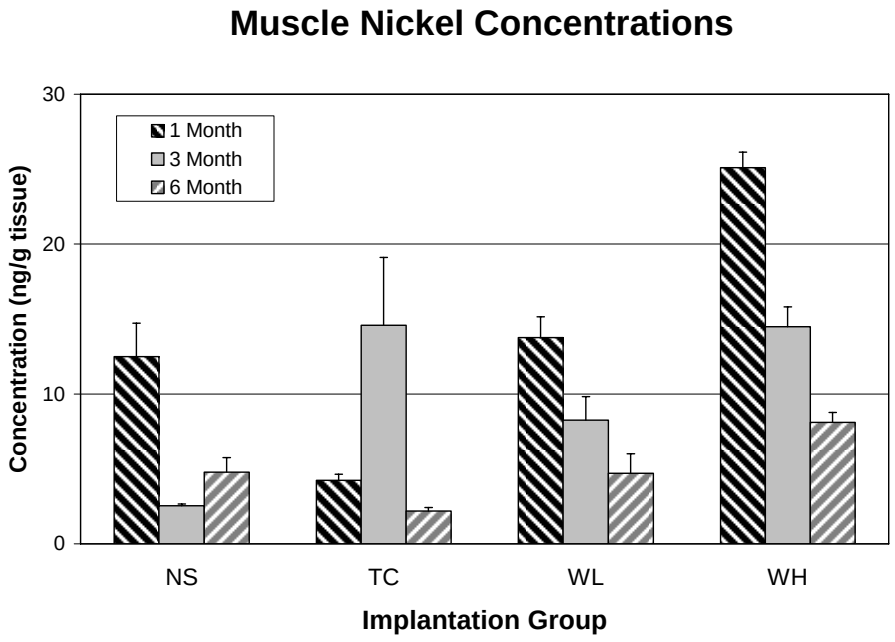
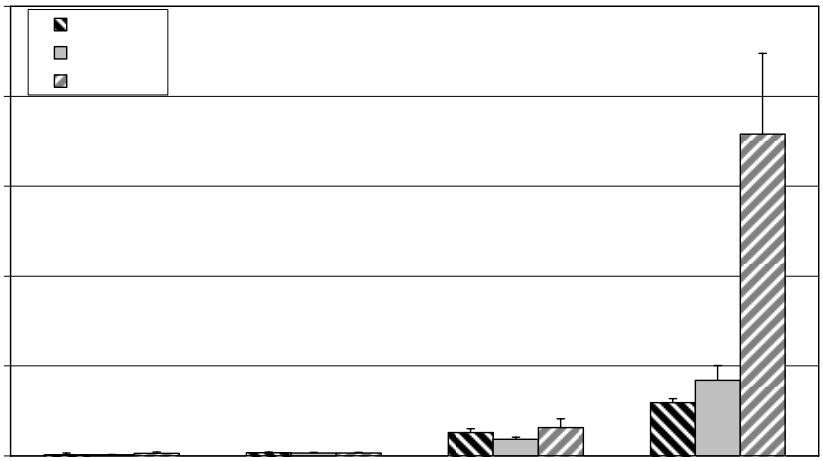
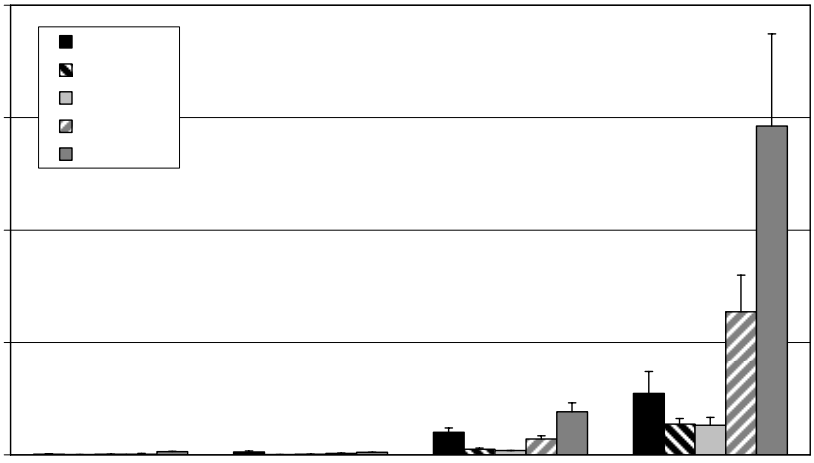


Figure 44. Muscle Cobalt (Panel A) and Nickel (Panel B) Concentrations over Time. Data are the mean of 10 independent samples. Error bars represent standard error of the mean. NS-non-surgical; TC-tantalum control; WL-tungsten alloy (low dose); WH-tungsten alloy (high dose).





A

Muscle Tungsten Concentratio

Embedded Weapons-Grade Tungsten Alloy Shrapnel Rapidly Induces Metastatic High-Grade Rhabdomyosarcomas in F344 Rats

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[1]Heavy Metals Research Team and [2]Veterinary Sciences Department, Armed Forces Radiobiology Research Institute, Bethesda, Maryland, USA; [3]Division of Veterinary Pathology, Walter Reed Army Institute of Research, Silver Spring, Maryland, USA

Continuing concern regarding the potential health and environmental effects of depleted uranium and lead has resulted in many countries adding tungsten alloy (WA)-based munitions to their battlefield arsenals as replacements for these metals. Because the alloys used in many munitions are relatively recent additions to the list of militarily relevant metals, very little is known about the health effects of these metals after internalization as embedded shrapnel. Previous work in this laboratory developed a rodent model system that mimicked shrapnel loads seen in wounded personnel from the 1991 Persian Gulf War. In the present study, we used that system and male F344 rats, implanted intramuscularly with pellets (1 mm × 2 mm cylinders) of weapons-grade WA, to simulate shrapnel wounds. Rats were implanted with 4 (low dose) or 20 pellets (high dose) of WA. Tantalum (20 pellets) and nickel (20 pellets) served as negative and positive controls, respectively. The high-dose WA-implanted rats (n = 46) developed extremely aggressive tumors surrounding the pellets within 4–5 months after implantation. The low-dose WA-implanted rats (n = 46) and nickel-implanted rats (n = 36) also developed tumors surrounding the pellets but at a slower rate. Rats implanted with tantalum (n = 46), an inert control metal, did not develop tumors. Tumor yield was 100% in both the low- and high-dose WA groups. The tumors, characterized as high-grade pleomorphic rhabdomyosarcomas by histopathology and immunohistochemical examination, rapidly metastasized to the lung and necessitated euthanasia of the animal. Significant hematologic changes, indicative of polycythemia, were also observed in the high-dose WA-implanted rats. These changes were apparent as early as 1 month postimplantation in the high-dose WA rats, well before any overt signs of tumor development. These results point out the need for further studies investigating the health effects of tungsten and tungsten-based alloys.

Key words: **cobalt, embedded fragment, nickel, rat, rhabdomyosarcoma, tungsten, tungsten alloy.** ***Environ Health Perspect*** **113:729–734 (2005). doi:10.1289/ehp.7791 available via *http://dx.doi.org/* [Online 15 February 2005]**

Tungsten has been used for many years in a variety of applications. Combining the hard, brittle tungsten metal with various other metals, including nickel and cobalt, produces tungsten alloys (WAs) with specific characteristics, some of which are of interest to the military. Recently, WAs have replaced lead in some small-caliber ammunition (the "green bullet") [Oak Ridge National Laboratory (ORNL) 1998] and depleted uranium (DU) in kinetic-energy penetrators (ORNL 1996). Based on a small number of studies, prevailing theory is that elemental tungsten or insoluble tungsten compounds have only limited toxicity (Leggett 1997). For example, tungsten coils implanted into the subclavian artery of rabbits rapidly degrade, leading to elevated serum tungsten levels as early as 15 min after implantation. However, after 4 months, no signs of local or systemic toxicity were observed (Peuster et al. 2003). Studies on health effects of Ni and Co are more numerous. Intramuscular injections (28 mg) of soluble metallic Ni or Co result in formation of rhabdomyosarcomas at the injection site. With Ni, 100% of injected rats develop a tumor within 41 weeks (Heath and Daniel 1964), whereas administration of Co results in tumor formation in 40% of the rats with a latency period of 71 weeks (Heath 1954, 1956). However, intramuscular implantation of rods or pellets composed of various Ni or Co alloys used in orthopedic prosthetics results in no excessive tumor formation (Gaechter et al. 1977; Sunderman 1989). A variety of other Ni compounds, including nickel subsulfide, nickel oxide, and nickel monosulfide, have been tested for carcinogenic potential via intramuscular administration (Gilman 1962; Sunderman and Maenza 1976; Sunderman et al. 1977). Tumors (rhabdomyosarcoma and fibrosarcoma) were found in many cases at the injection site, with tumor yield dependent on solubility and concentration of the administered compound. It has been postulated that the yield of localized tumors is inversely related to the rate of solubilization of the Ni-containing compound (Kasprzak et al. 1983). This hypothesis does not appear to hold for Co compounds (Lison et al. 2001).

Metal alloys present additional problems when investigating health effects. The various metals comprising the alloy, as well as the method of production, can all factor into the overall health effect observed upon exposure. Investigations on hard-metal disease have shown that either tungsten carbide or Co alone has limited toxicity on lung tissue (Lasfargues et al. 1992). However, when combined, the tungsten carbide/cobalt mixture acts synergistically to increase the observed toxicity. It is not known whether this is due to the combined toxicity of the tungsten carbide/cobalt mixture or to an increase in the bioavailability of the known toxicant, Co (Lison and Lauwerys 1997). *In vitro* studies investigating malignant transformation of immortalized human cells by mixtures of tungsten, Ni, and Co suggest a synergistic effect that greatly exceeds the effects of the metals individually (Miller et al. 2001, 2002).

Advancements in metallurgy have led the military of many nations to replace DU in some armor-penetrating munitions and lead in small-caliber ammunition with various alloys of tungsten. One motivation for such a replacement is widespread public concern about the health and environmental impact of continued use of these metals. However, to our knowledge, none of these militarily relevant WAs has been tested for potential health effects, especially as embedded shrapnel. There is a growing list of health concerns related to tungsten exposure. Although a definitive link has not been established, several cancer clusters in the United States are associated with elevated levels of tungsten in the environment. Those findings, along with the results presented in this article, raise questions about the possible consequences of tungsten exposure. More important, these results raise extremely serious concerns over the potential health effects of WA-based munitions currently being used as nontoxic alternatives to lead and DU.

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Materials and Methods

Rodents. Male F344 rats (6 weeks of age; Harlan, Frederick, MD) were maintained in a facility accredited by the Association of Assessment and Accreditation of Laboratory Animal Care in accordance with the *Guide for the Care and Use of Laboratory Animals* (Institute of Laboratory Animal Resources 1996). All procedures, including euthanasia criteria (Tomasovic et al. 1988), were approved by the Armed Forces Radiobiology Research Institute's (AFRRI) Animal Care and Use Committee. Upon arrival, animals were screened for common rodent pathogens. Rats were pair-housed in plastic microisolator cages with hardwood chips for bedding and fed a certified NTP-2000 (Quality Lab Products, Elkridge, MD) diet (Rao 1996) with acidified water provided *ad libitum*. Animals were on a 12-hr light/dark cycle with no twilight and were weighed weekly.

Pellets. All metal pellets were cylinders 1 mm in diameter and 2 mm in length. Nickel (99.995% metallic Ni) and tantalum (99.95% Ta) pellets were purchased from Alfa Aesar (Ward Hill, MA). WA pellets were fabricated by Aerojet Ordnance Tennessee (Jonesborough, TN) using standard kinetic energy penetrator production processes. An average WA pellet weighed 27.5 mg and consisted of 91.1% tungsten, 6.0% Ni, and 2.9% Co. Ni and Ta pellets weighed 14 mg and 27 mg, respectively. Before implantation surgery, all pellets were cleaned and chemically sterilized (Pellmar et al. 1999).

Pellet-implantation surgery. A rodent model system (AFRRI 1996), originally developed to mimic DU shrapnel loads seen in wounded personnel from the 1991 Persian Gulf War, was used to investigate the health effects of retained WA shrapnel. All rats were implanted with a total of 20 pellets split evenly between each hind leg. Experimental groups included Ta (negative control, 20 Ta pellets), low-dose WA (4 WA pellets and 16 Ta pellets), high-dose WA (20 WA pellets), and Ni (positive control, 20 Ni pellets). Tantalum was used as a negative implantation control because it is considered inert and has been used in human prostheses (Hockley et al. 1990; Johansson et al. 1990). Nickel, a known carcinogen, was used as a positive control (Costa and Klein 1999; Kasprzak et al. 2003). Rats were implanted at 9 weeks of age. For the pellet implantation procedure, anesthesia was induced by continuous administration of isoflurane using an open circuit system with a scavenger/recapture system. All surgery was done using aseptic techniques. After the surgical sites were clipped and cleansed with Betadine, an incision was made through the skin to expose the gastrocnemius muscle. Pellets were implanted in the muscle, spaced approximately 1.5 mm apart on the lateral side of each leg. The incision was closed with sutures and tissue adhesive. Rats were closely monitored after surgery until they were ambulatory. An analgesic (buprenorphine hydrochloride; Reckitt and Colman, Hull, UK) was administered preoperatively and then as needed postoperatively. The surgical sites were examined daily for signs of inflammation, infection, and local metal toxicity.

Experimental groups. Our pellet implantation groups included Ta (negative control), WA (both a low- and high-dose group), and Ni (positive control). The original euthanasia time points were to be 1, 3, 6, 12, 18, and 24 months; however, because of the rapid tumor development, no WA- or Ni-implanted rat survived much past 6 months postimplantation. Final survival data therefore included rats originally assigned to the 12-, 18-, and 24-month experimental groups, whose animals died earlier than those designated time points. This resulted in group sizes of $n = 46$ for the Ta and both WA groups, and $n = 36$ for the Ni group. Hematologic assessments were conducted on the separate 1-, 3-, and 6-month WA implantation groups.

Pathology. At various times postimplantation or when moribund, rats were euthanized by isoflurane overdose. A complete gross pathology examination was conducted, noting any abnormalities, and tissues were collected for analysis. Weights of representative tissues, including spleen, thymus, testes, kidney, and liver, were determined and normalized to body weight. Tissues for histopathology were fixed in buffered formalin, processed and embedded in paraffin, cut at 5–6 µm, mounted, and stained with hematoxylin and eosin (H&E). Immunohistochemical analysis was conducted on 5-µm-thick sections of formalin-fixed, paraffinized tissue. After deparaffination and rehydration, nonspecific binding was blocked with Power Block (Biogenex, San

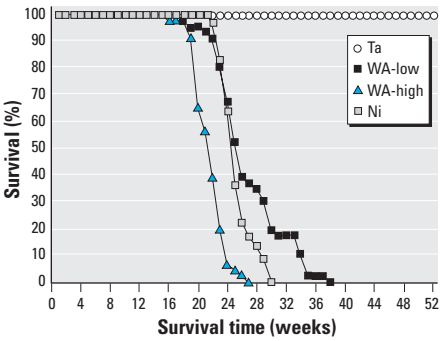

Figure 1. Survival times of pellet-implanted rats.

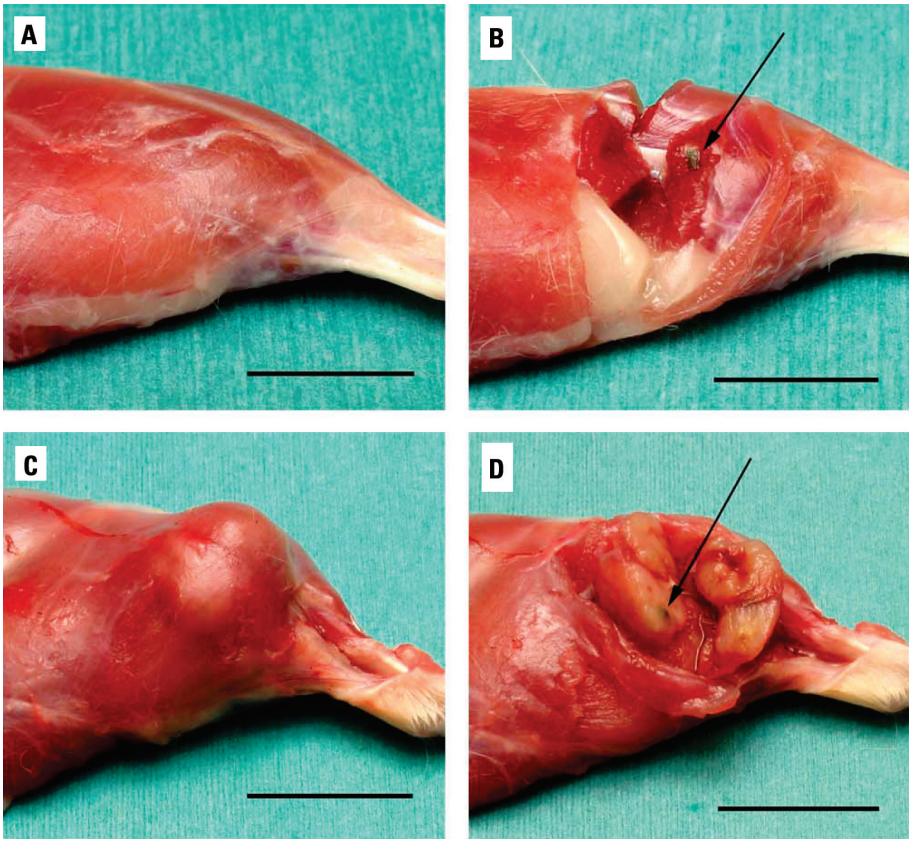

Figure 2. Effect of implanted WA pellets on F344 rats. (*A*) Gross appearance of Ta-implanted hind leg. (*B*) Dissected area around implanted Ta pellet (arrow indicates pellet). (*C*) Gross appearance of WA-implanted hind leg with tumor(s). (*D*) Dissected area around implanted WA pellet with tumor surrounding pellet (arrow indicates pellet). Bar = 2 cm.

Ramon, CA). The tissue was then reacted with prediluted rabbit anti-desmin polyclonal antibody (Biogenex) and treated with biotinylated secondary anti-rabbit antibody (Biogenex). After blocking with hydrogen peroxide, the tissue sections were labeled with peroxidase-conjugated streptavidin (Biogenex) and aminoethyl carbazole (AEC; Biogenex) was used as a chromogen. Slides were then counterstained with hematoxylin and mounted.

Hematology. At euthanasia, we obtained blood for hematologic assessments from the abdominal aorta of isoflurane-anesthetized rats using a heparinized needle and sample tubes containing EDTA (Becton-Dickinson, Franklin Lakes, NJ). We determined white and red blood cell counts; hemoglobin; hematocrit; mean corpuscular volume, hemoglobin, and hemoglobin concentration; red cell distribution width; platelet counts and volume; and neutrophil, lymphocyte, monocyte, eosinophil, and basophil counts with a Bayer Advia 120 Hematology Analyzer (Bayer Diagnostics, Terrytown, NY).

Results

All rats tolerated the pellet implantation procedure with no apparent adverse effects. The incision sites were examined daily; no rat showed any signs of infection from the surgery, or any discomfort postoperatively. Body weights were recorded weekly. Once they had recovered from the surgical procedure, all rats gained weight at equivalent rates. However, in the first week after the pellet implantation surgery, the rate of weight gain by the Ta and low-dose WA rats was slower than normal, and high-dose WA and Ni rats lost weight. This was followed by large weight gains in postimplantation week 2 in all experimental groups. There were no statistical differences in rate of body weight gain between any of the groups throughout the remaining experimental period. As previously reported, the implantation and retention of cylindrical metal pellets (1 mm × 2 mm) had no effect on locomotive abilities in rats (AFRRI 1996; Pellmar et al. 1999), nor did we observe any such difficulties in this study.

At approximately 16–20 weeks postimplantation, we began to observe tumors at the pellet implantation sites in the WA and Ni rats. In some high-dose WA animals, palpable tumors were apparent as early as 14 weeks postimplantation. Tumors developed rapidly in WA-implanted animals. The tumors were aggressive and fast growing, necessitating euthanasia of the animals several weeks later. On the basis of previously published literature (Heath and Daniel 1964), we expected the Ni-implanted positive control rats to develop tumors at the implantation site, but the speed at which the tumors developed was surprising: approximately 5 months after implantation.

Figure 1 shows the percentage of surviving animals as a function of time after pellet implantation. Rats implanted with Ta pellets (n = 46) survived well beyond 12 months with no apparent health problems. All rats in the high- and low-WA and the Ni groups developed tumors and were euthanized upon becoming moribund. Rats in the high-dose WA group (n = 46) survived the least amount of time (mean survival time ± SD = 21.8 ± 2.1 weeks). Nickel-implanted animals (n = 36) and the low-dose WA group (n = 46) survived slightly longer, with mean (± SD) survival times of 25.4 ± 2.1 and 27.0 ± 4.6 weeks, respectively. The mean survival time of the high-dose WA animals was significantly shorter than that of the low-dose WA- or Ni-implanted animals [analysis of variance (ANOVA) followed by Dunnett's test, $p < 0.05$]. The mean survival times of the low-dose WA- and the Ni-implanted animals were not statistically different from each other. The

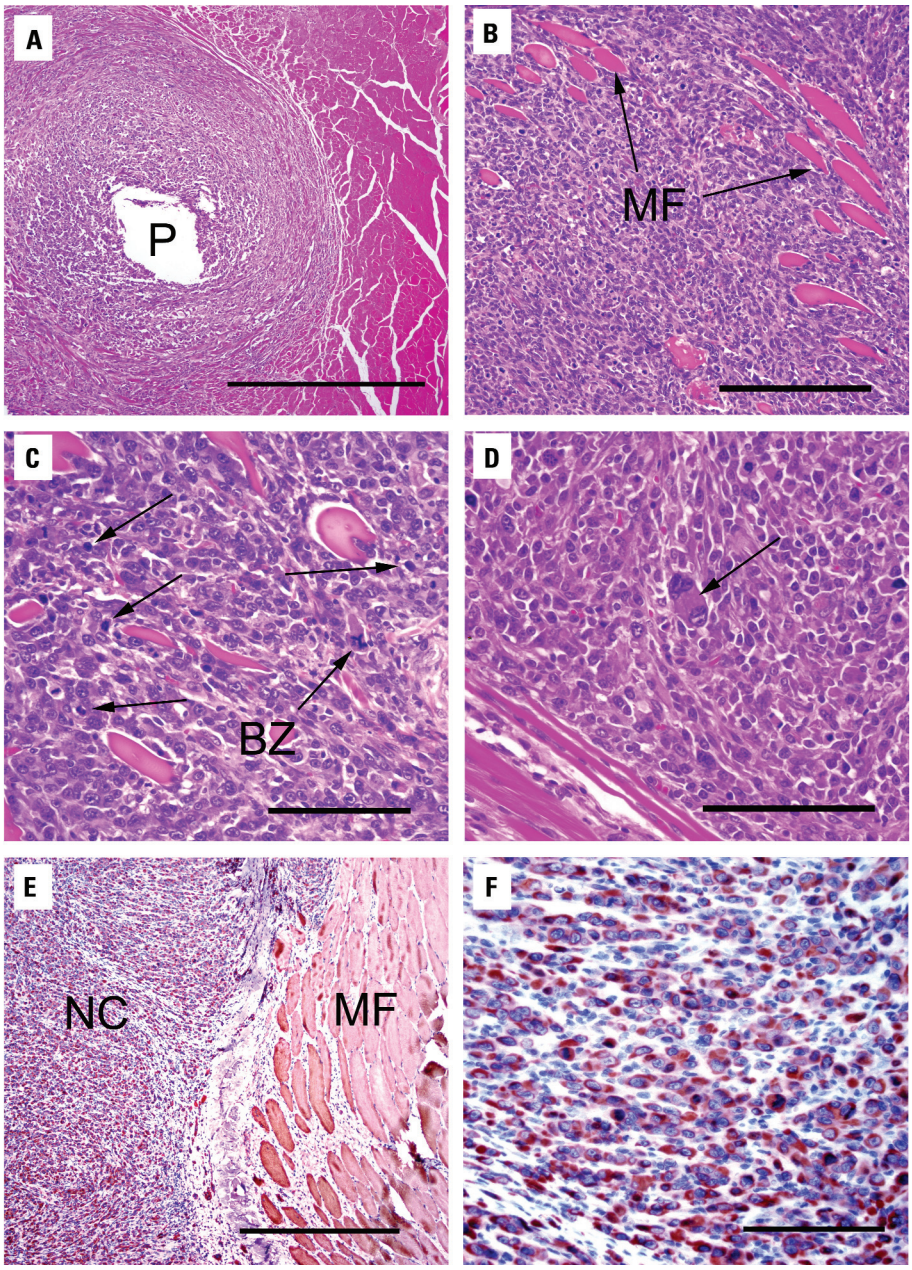

Figure 3. Histopathologic examination of leg tumor surrounding WA pellet. (*A*) H&E-stained section of leg tumor from F344 rat showing WA pellet hole (P); bar = 500 µm. (*B*) H&E-stained tumor section showing neoplastic infiltration of preexisting muscle fibers (MF); bar = 200 µm. (*C*) H&E-stained tumor section showing neoplastic cells with numerous mitoses (arrows) and bizarre mitotic figures (BZ); bar = 100 µm. (*D*) H&E-stained tumor section showing pleomorphic cell (arrow); bar = 100 µm. (*E*) Desmin staining of leg tumor showing neoplastic cells (NC) and muscle fibers (MF); bar = 500 µm. (*F*) Desmin staining of neoplastic cells; bar = 50 µm.

results reported here are part of a larger study that also investigated the health effect of embedded DU fragments. We did not observe tumor formation in the DU-implanted rats (Kalinich JF, Miller AC, McClain DE, unpublished data).

Upon euthanasia, the animals underwent necropsy, and tissue samples were taken for various analyses. Figure 2 shows the appearance of the hind limb of rats implanted with Ta (Figure 2A) or WA (Figure 2C) for 26 and 23 weeks, respectively, before surgical removal of the implanted pellets. The gross anatomy of the Ta-implanted leg is normal, whereas in the WA leg the tumor is clearly visible. Upon dissection, no obvious abnormalities were observed in the Ta-implanted animals, and the pellets could be easily removed (Figure 2B). However, in the WA-implanted animals, the pellets were surrounded by tumor (Figure 2D). In many cases, the interior of the tumor had become necrotic and/or hemorrhagic. Similar tumors were found for both WA- and Ni-implanted animals. In low-dose WA animals, tumors were found surrounding the WA pellets only. No tumors were found surrounding implanted Ta pellets. Implanted WA pellets rapidly oxidized and had a slightly eroded appearance. Ta pellets did not have an eroded appearance even after implantation for 6 months. However, despite their appearance, the WA pellets lost < 5% of their mass over this time.

Tumor tissue was histopathologically examined and characterized. Figure 3A shows the neoplastic cells surrounding the site of the implanted WA pellet. These cells infiltrated preexisting skeletal muscle fibers. Fibers that became isolated by this process degenerated and demonstrated a loss of cross-striations and internalization of nuclei (Figure 3B,C). Neoplastic cells were pleomorphic with marked anisocytosis and anisokaryosis (Figure 3D). In addition, an extremely high mitotic rate was observed in these cells, and bizarre mitoses were present. Immunohistochemical staining was used to determine the origin of these neoplastic cells. The cells were strongly positive for desmin (Figure 3E,F), suggesting a skeletal muscle origin.

In the WA-implanted animals, the tumors had metastasized to the lung. None of the Ni-implanted animals showed signs of lung metastases, although some exhibited endogenous histiocytic lipid pneumonia not seen in the WA animals. Figure 4A shows numerous metastatic foci in the lungs of a high-dose WA rat. These multiple masses obscure > 50% of the lung surface and up to 90% in the latter stages of development. Figure 4B shows a photomicrograph of these pulmonary metastases. Apparent is the multifocal, vascular orientation of these neoplasms. There are neoplastic cells surrounding the arterioles and bronchioles, expanding the alveolar septae, and replacing alveolar spaces. These neoplastic cells have a high mitotic rate and are often seen surrounding or occluding arterioles (Figure 4C). Figure 4D shows that the metastatic neoplastic cells, as well as vascular and airway smooth muscle, are strongly positive for the muscle marker desmin.

Selected hematologic and organ weight parameters for euthanized rats are shown in Table 1. The Ta data were obtained from rats implanted with Ta pellets for 6 months. The data for the remaining groups were obtained at the time the rats became moribund because of tumor development. No significant differences in organ/body weight ratios were seen for the low-dose WA- or Ni-implanted animals compared with Ta-implanted control rats. However, high-dose WA-implanted rats showed significantly higher spleen:body weight ratios compared with control rats. In addition, thymus:body weight ratios were decreased in the high-dose WA rats. Because the spleen and thymus are integral components of the immune system, these changes suggest that embedded WA, at certain levels, may be immunotoxic. The kidney:body weight ratio for high-dose WA rats was also significantly higher than that of Ta-implanted rats. High-dose WA rats euthanized 1 and 3 months after pellet implantation also exhibited significantly elevated spleen:body weight ratios compared with the appropriate Ta-implanted control rats (Tables 2 and 3). Thymus:body weight ratios, however, were not significantly different. At 3 months postimplantation, the kidney:body weight ratio in high-dose WA rats was significantly higher than that in Ta rats, but it was significantly lower at 1 month postimplantation. There were no 1- and 3-month Ni-implanted groups.

WA-implanted animals had significant changes in a number of hematologic parameters. Rats implanted with 20 WA pellets exhibited significant increases in white blood cell counts, red blood cell counts, hemoglobin, and hematocrit levels compared with Ta control rats, whereas rats implanted with 20 Ni pellets had significant decreases in red blood cell counts, hemoglobin, and hematocrit levels (Table 1). Hematologic parameters from low-dose WA rats were not statistically different from controls. Statistically significant increases in red blood counts, hemoglobin, and hematocrit levels were observed in high-dose WA animals as early as 1 month after pellet implantation and persisted throughout

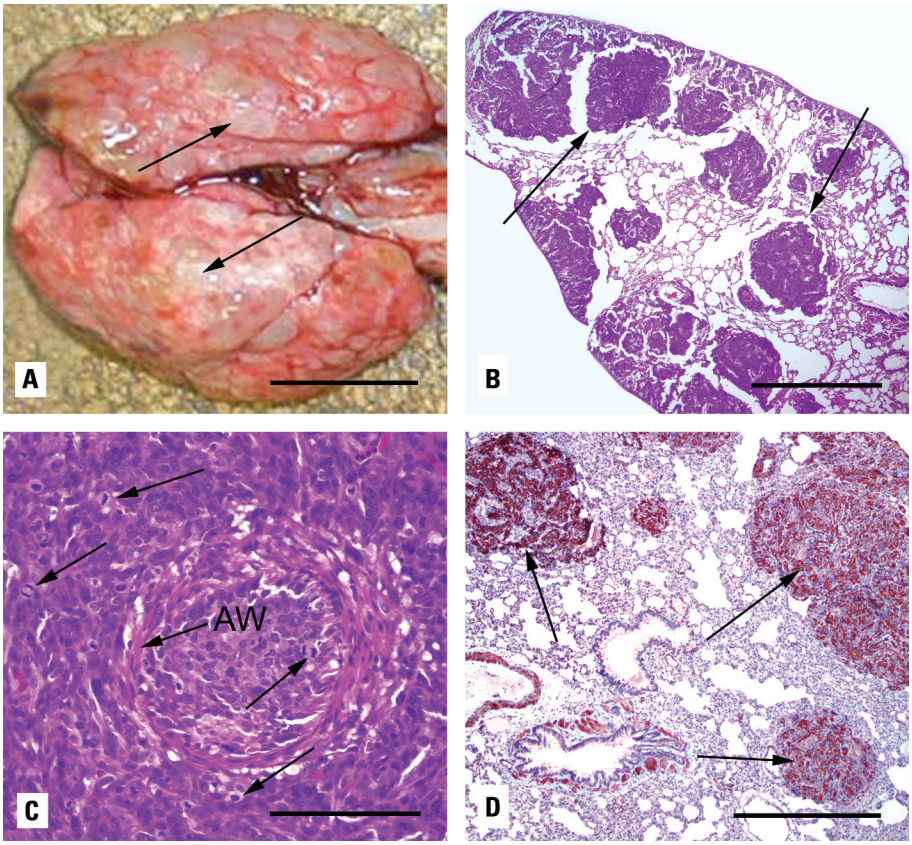

Figure 4. Lung metastases from WA-implanted F344 rats. (*A*) Gross appearance of pulmonary metastases from WA-implanted rat (arrows indicate metastatic foci); bar = 1 cm. (*B*) H&E-stained section of pulmonary metastases (arrows); bar = 1 mm. (*C*) H&E-stained section of an occluded pulmonary arteriole [arrow indicates vascular smooth muscle wall (AW)] showing neoplastic cells with numerous mitoses (arrows); bar = 50 µm. (*D*) Desmin staining of pulmonary metastases (arrows); bar = 500 µm.

the experimental period (Tables 2 and 3). In addition, there were statistically significant increases in the numbers of neutrophils, lymphocytes, monocytes, and eosinophils present in high-dose WA animals. Low-dose WA animals had elevated neutrophil, lymphocyte, and monocyte numbers at 3 months postimplantation, but only the neutrophil numbers were statistically different from the controls at the 5–6 month euthanasia point. The Ni-implanted animals had significantly lower lymphocyte counts than the controls. All other parameters were statistically identical to the controls. These results suggest there is a dose-dependent perturbation in many hematology parameters as a result of an increasing WA pellet number.

Discussion

Tungsten-based alloys are currently being used as replacements for DU in kinetic-energy penetrators and for lead in small-caliber ammunition. However, the health effects of these unique alloys have not been investigated, especially in the case of embedded fragments such as shrapnel wounds. In this study, using male F344 rats and a system designed to investigate the effects of embedded metal fragments (AFRRI 1996), we have shown the embedded weapons-grade WA (91.1% W, 6.0% Ni, 2.9% Co) results in rapid tumor formation at the implantation site in 100% of the rats. The rate of tumor formation correlates with pellet number. Ni-implanted rats also develop tumors at the implantation site, although not as rapidly as seen with WA. Histopathologic and immunohistochemical data support a diagnosis of a pleomorphic rhabdomyosarcoma for both the WA- and Ni-induced leg tumors (Altmannsberger et al. 1985).

Rats implanted with 20 WA pellets (high-dose WA) showed significantly increased spleen:body weight ratios compared with Ta control rats. Low-dose WA rats (four WA pellets) also exhibited increased spleen:body weight ratios, but these increases were not statistically significant (ANOVA followed by Dunnett's test). Values for Ni-implanted rats were identical to control rats. The spleen changes observed in the high-dose WA rats were apparent as early as 1 month after pellet implantation. Once again, low-dose WA rats showed increased, but not statistically significant, spleen:body weight ratios. With the exception of the spleen, the only other organ:body weight perturbations were seen in high-dose WA rats and included a decrease in thymus:body weight ratio at approximately 5 months and changes in kidney:body weight ratios. The 1-month kidney:body weight ratio for high-dose WA rats was significantly lower

Table 1. Selected hematologic and organ weight parameters (mean ± SEM) for euthanized rats.

	Ta	WA (low)	WA (high)	Ni
White blood cells (10^3/μL)	3.19 ± 0.24	3.95 ± 0.43	4.56 ± 0.29*	2.56 ± 0.20
Red blood cells (10^6/μL)	8.32 ± 0.09	8.03 ± 0.19	10.10 ± 0.07**	7.46 ± 0.13**
Hemoglobin (g/dL)	14.50 ± 0.13	13.90 ± 0.36	16.46 ± 0.30**	12.95 ± 0.23**
Hematocrit (%)	41.77 ± 0.53	40.38 ± 0.96	50.18 ± 0.39**	38.12 ± 0.77**
MCV (fL)	50.22 ± 0.16	50.26 ± 0.28	49.71 ± 0.16	51.08 ± 0.66
MCH (pg)	17.46 ± 0.15	17.31 ± 0.13	16.30 ± 0.28**	17.35 ± 0.08
MCHC (g/dL)	34.77 ± 0.36	34.46 ± 0.32	32.81 ± 0.62**	34.05 ± 0.50
RDW (%)	12.54 ± 0.09	13.07 ± 0.11**	13.77 ± 0.09**	13.04 ± 0.16*
Platelets (10^3/μL)	562.00 ± 14.72	542.05 ± 14.27	467.50 ± 17.57**	487.18 ± 26.10*
MPV (fL)	9.93 ± 0.69	8.64 ± 0.52	10.13 ± 0.62	8.97 ± 0.52
Neutrophils (10^3/μL)	0.79 ± 0.05	1.03 ± 0.09*	1.31 ± 0.12**	0.78 ± 0.09
Lymphocytes (10^3/μL)	2.21 ± 0.18	2.42 ± 0.17	2.95 ± 0.23*	1.63 ± 0.12*
Monocytes (10^3/μL)	0.07 ± 0.01	0.09 ± 0.02	0.13 ± 0.02*	0.05 ± 0.01
Eosinophils (10^3/μL)	0.08 ± 0.01	0.08 ± 0.01	0.12 ± 0.01**	0.06 ± 0.01
Basophils (10^3/μL)	0.02 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.02 ± 0.00
Spleen (mg/g bw)	2.18 ± 0.10	2.30 ± 0.08	2.60 ± 0.06**	2.17 ± 0.05
Thymus (mg/g bw)	0.86 ± 0.03	0.76 ± 0.04	0.70 ± 0.04*	0.74 ± 0.07
Liver (mg/g bw)	29.21 ± 0.28	29.39 ± 0.24	28.77 ± 0.35	29.52 ± 0.39
Kidney (mg/g bw)	5.13 ± 0.06	5.13 ± 0.06	5.36 ± 0.05*	5.15 ± 0.08
Testes (mg/g bw)	7.31 ± 0.07	7.20 ± 0.08	7.40 ± 0.10	7.21 ± 0.14

Abbreviations: bw, body weight; MCH, mean corpuscular hemoglobin; MCHC, mean corpuscular hemoglobin concentration; MCV, mean corpuscular volume; MPV, mean platelet volume; RDW, red blood cell distribution width. Data represent mean ± SEM of 20 observations (10 for Ni group).
*$p < 0.05$, and **$p < 0.01$ compared with the Ta control group by one-way ANOVA followed by Dunnett's test for group mean comparisons.

Table 2. Selected hematologic and organ weight parameters (mean ± SEM) for rats implanted with metal pellets for 3 months.

	Ta	WA (low)	WA (high)
White blood cells (10^3/μL)	2.88 ± 0.20	4.06 ± 0.14**	4.01 ± 0.21**
Red blood cells (10^6/μL)	7.48 ± 0.06	8.48 ± 0.15*	9.10 ± 0.70**
Hemoglobin (g/dL)	12.90 ± 0.09	15.48 ± 0.35*	17.29 ± 0.15**
Hematocrit (%)	38.10 ± 0.27	42.14 ± 0.73*	44.79 ± 0.62**
MCV (fL)	50.96 ± 0.45	49.70 ± 0.09	48.87 ± 0.39
MCH (pg)	17.26 ± 0.12	18.27 ± 0.17	17.65 ± 0.12
MCHC (g/dL)	33.84 ± 0.35	36.71 ± 0.31**	35.89 ± 0.31**
RDW (%)	12.82 ± 0.33	12.68 ± 0.12	13.61 ± 0.09**
Platelets (10^3/μL)	513.20 ± 38.36	585.11 ± 35.87	568.29 ± 8.82
MPV (fL)	9.58 ± 1.13	9.14 ± 0.59	11.74 ± 0.51
Neutrophils (10^3/μL)	0.62 ± 0.04	0.79 ± 0.03*	0.91 ± 0.08*
Lymphocytes (10^3/μL)	2.10 ± 0.16	3.06 ± 0.14*	2.82 ± 0.17*
Monocytes (10^3/μL)	0.04 ± 0.01	0.07 ± 0.01*	0.08 ± 0.01*
Eosinophils (10^3/μL)	0.09 ± 0.01	0.09 ± 0.01	0.09 ± 0.01
Basophils (10^3/μL)	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.00
Spleen (mg/g bw)	2.07 ± 0.03	2.16 ± 0.03	2.50 ± 0.03**
Thymus (mg/g bw)	0.73 ± 0.03	0.84 ± 0.03	0.70 ± 0.04
Liver (mg/g bw)	30.58 ± 0.33	31.00 ± 0.33	30.27 ± 0.31
Kidney (mg/g bw)	5.43 ± 0.06	5.73 ± 0.23	5.76 ± 0.04**
Testes (mg/g bw)	8.34 ± 0.12	8.21 ± 0.46	8.42 ± 0.18

Abbreviations: bw, body weight; MCH, mean corpuscular hemoglobin; MCHC, mean corpuscular hemoglobin concentration; MCV, mean corpuscular volume; MPV, mean platelet volume; RDW, red blood cell distribution width. Data represent mean ± SEM of 15 observations.
*$p < 0.05$, and **$p < 0.01$ compared with the age-matched Ta control group by one-way ANOVA followed by Dunnett's test for group mean comparisons.

Table 3. Selected hematologic and organ weight parameters (mean ± SEM) for rats implanted with metal pellets for 1 month.

	Ta	WA (low)	WA (high)
White blood cells (10^3/μL)	3.86 ± 0.20	3.81 ± 0.14	3.86 ± 0.21
Red blood cells (10^6/μL)	7.84 ± 0.08	7.74 ± 0.07	8.50 ± 0.07**
Hemoglobin (g/dL)	13.65 ± 0.15	14.81 ± 0.16	15.84 ± 0.14**
Hematocrit (%)	40.15 ± 0.42	39.66 ± 0.50	43.29 ± 0.35**
MCV (fL)	51.20 ± 0.14	51.22 ± 0.31	50.98 ± 0.19
MCH (pg)	17.41 ± 0.05	19.12 ± 0.09	18.64 ± 0.19**
MCHC (g/dL)	34.01 ± 0.12	37.37 ± 0.29	36.56 ± 0.41**
RDW (%)	12.21 ± 0.11	12.69 ± 0.11	14.18 ± 0.18**
Platelets (10^3/μL)	646.50 ± 18.76	641.00 ± 17.97	756.20 ± 43.48*
MPV (fL)	7.91 ± 0.40	8.56 ± 0.39	9.90 ± 0.55*
Neutrophils (10^3/μL)	0.65 ± 0.04	0.79 ± 0.05	0.81 ± 0.04**
Lymphocytes (10^3/μL)	3.04 ± 0.18	2.85 ± 0.13	2.90 ± 0.18
Monocytes (10^3/μL)	0.06 ± 0.00	0.06 ± 0.01	0.07 ± 0.00
Eosinophils (10^3/μL)	0.07 ± 0.01	0.08 ± 0.01	0.05 ± 0.00*
Basophils (10^3/μL)	0.02 ± 0.00	0.02 ± 0.00	0.01 ± 0.00
Spleen (mg/g bw)	2.37 ± 0.06	2.42 ± 0.05	2.73 ± 0.04**
Thymus (mg/g bw)	1.07 ± 0.03	1.14 ± 0.04	1.06 ± 0.03
Liver ((mg/g bw)	34.47 ± 0.26	34.31 ± 0.22	34.18 ± 0.61
Kidney (mg/g bw)	6.17 ± 0.08	6.06 ± 0.06	5.91 ± 0.05*
Testes (mg/g bw)	10.10 ± 0.16	9.86 ± 0.13	9.98 ± 0.11

Abbreviations: bw, body weight; MCH, mean corpuscular hemoglobin; MCHC, mean corpuscular hemoglobin concentration; MCV, mean corpuscular volume; MPV, mean platelet volume; RDW, red blood cell distribution width. Data represent mean ± SEM of 15 observations.
*$p < 0.05$, and **$p < 0.01$ compared with the age-matched Ta control group by one-way ANOVA followed by Dunnett's test for group mean comparisons.

than control. However, from 3 months on, these ratios were significantly higher than control. It is possible that the lower kidney weights at 1 month postimplantation represent a toxic response to the heavy metals from the implanted pellets, but by 3 months and later, the kidney has begun to respond in a different manner. Although there were no gross abnormalities of the kidney at necropsy, we continue to investigate this observation.

A variety of hematologic changes were observed in WA- and Ni-implanted rats. Ni-implanted rats showed a significant decrease in red blood cells, hemoglobin, and hematocrit at the time of morbidity, indicating possible Ni-induced anemia. For low-dose WA rats the hematologic changes, including significant increases in red blood cells, white blood cells, hemoglobin, hematocrit, neutrophils, lymphocytes, and monocytes, peaked at 3 months postimplantation and returned to normal by 5–6 months. High-dose WA rats demonstrated the same changes observed in low-dose WA rats, but they occurred much more rapidly (as early as 1 month postimplantation) and persisted throughout the life of the animal. The splenomegaly and hematologic changes observed in these rats are suggestive of polycythemia. Cobalt has been used experimentally to induce polycythemia in rats (Endoh et al. 2000; Rakusan et al. 2001), although the concentration required is far greater than found in the WA pellets. In addition, the speed at which these hematologic changes occurred in the high-dose WA rats was also surprising. These results suggest a dose-dependent perturbation in many hematology parameters as a result of an increasing WA pellet number.

The search for munitions that are considered environmentally friendly yet still retain their military effectiveness has led to the appearance of many unique alloys on the modern battlefield. Often, decisions on the health consequences of exposure (inhalation, ingestion, wound contamination, etc.) to these specific alloys are based on studies that investigated only one specific metal of the alloy rather than the particular alloy in question. Tungsten-based munitions are a recent addition to many countries' arsenals, primarily in response to the continuing concerns regarding the potential environmental and health effects of DU in kinetic-energy penetrators and of lead in small-caliber ammunition. For years, exposure to tungsten was thought to be of little consequence to health. In fact, tungsten is occasionally found as a minor component in some of the various alloys used to produce medical implant devices such as artificial hips and knees. The tungsten concentration in these alloys ranges from 5% to 15%. Because the alloy used in WA munitions usually contains > 90% tungsten, along with smaller amounts of other metals, it was also assumed that exposure to these alloys would present little or no health risk. As we have shown here, this is not the case in our rodent model. Embedded WA pellets not only resulted in aggressive, metastatic, pleomorphic rhabdomyosarcomas, but also caused significant hematopoietic changes well before the carcinogenic effect was observed. It seems unlikely that these adverse health effects can be attributed solely to the small amounts of Ni and/or Co present in the alloy. The tumors induced by the 100% Ni implants occurred later than those induced by the alloys containing 6% Ni. However, recent *in vitro* studies have demonstrated a synergistic effect in terms of damage when tungsten is present with these metals (Miller et al. 2001, 2002).

The mechanism of the effects reported here with embedded WA pellets remains unclear. Despite the fact that the smooth and impermeable surface of the pellets represent characteristics known capable of inducing foreign-body or solid-state carcinogenesis (Bates and Klein 1966; Brand et al. 1975), this process is unlikely to have occurred in our experiments because implanted Ta pellets of an identical geometry and surface resulted in no tumor formation. One possibility is that free-radical reactions at the interface of the pellet and tissue could result in damage leading to carcinogenesis. Recently, the role of tungsten in human health and disease has come under increased scrutiny. Environmental testing of the leukemia cluster around Fallon, Nevada, in the United States showed slightly elevated levels of several heavy metals including uranium and Co but significantly elevated levels of tungsten [Centers for Disease Control and Prevention (CDC) 2003]. Although no definitive link between elevated tungsten levels and cancer has been established, because of the uncertainty surrounding this issue, the U.S. National Toxicology Program recently added tungsten to their list of compounds to be assessed for adverse health effects. Further study of the health effect of tungsten and WAs is clearly indicated.

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