Improving the Performance of Medical Implants with Carbon Nanotubes

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(Although outside the ‘norm’ of most Energeia features, this article does discuss uses for carbon nanotubes. Also, it is about a subject many readers may be facing soon – aging – and new methods to hold us together. – MM)

When Sir John Charnley, a renowned British orthopaedic surgeon, first conceived the notion of surgically replacing a patient’s degenerative joint by anchoring artificial components to the skeletal system with acrylic bone cement, I doubt he envisioned the enormous impact his surgical technique would have on millions of lives around the world. This procedure, which he performed regularly in 1961, was so successful at alleviating patient discomfort that doctors traveled from all ends of the earth to learn the technique firsthand.

The anatomy of a total joint replacement is simple. First, the degenerative portions of the skeletal system that form the joint (e.g. femoral head and acetabular cup of the hip) are surgically removed. Next, new components of metal, ceramic, or polymer that resemble the size and shape of the joint are implanted into the skeletal system. The artificial components are designed to provide seemingly friction-less movement that mimics synovial joint movement in the body. In some cases, the artificial components are “cemented” in the implant site; that is, they are anchored to the patient’s bone with a layer of acrylic bone cement.

Acrylic bone cement is a proven, polymer-based material. It is attractive for orthopaedic surgery because it can be injected into the exposed intermedullary canal of the bone and it hardens within a reasonable amount of time. Technically, the term “bone cement” is a misnomer. The function of this polymer is not to bind the materials together, but rather it mechanically stabilizes the implanted components within the patient’s bone. The hardened bone cement creates a buffer zone between the stiff implant and the less stiff bone. The bone cement layer, also known as the bone cement mantle, enables adequate distribution of joint reaction and body forces from the implant to the bone.

Charnley used bone cement as a key component of total hip arthroplasty replacements nearly fifty years ago. He understood that when the liquid and powder components of the bone cement system are mixed, a doughy material is formed. The bone cement dough was injected into the clean intermedullary canal of the patient’s femur. He then inserted the stem of the artificial femoral component into the dough and positioned the implant to his satisfaction. Once hardened, the bone cement stabilized the new implant restoring function to the hip joint. To Charnley’s
Carbon Nanotubes (cont.)
credit, acrylic bone cement celebrates an admirable track record that spans many decades.

There are some drawbacks to bone cement that affect the clinical life of the implant. For example, acrylic bone cement mantle is susceptible to fatigue failure. Fatigue is an engineering term used to describe the damage effects of loading and unloading a material repeatedly over long periods of time. The bone cement mantle (especially in hip and knee arthroplasties) is fatigued during everyday activities such as sitting and standing, walking, and climbing stairs.

Over time, the bone cement mantle becomes filled with microscopic cracks. Eventually, these cracks coalesce into one larger fatigue crack, which progresses through the thickness of the bone cement mantle until catastrophic failure occurs. Failure of the bone cement ultimately leads to implant loosening and joint destabilization. This is one of the leading causes of clinical failure, a problem that must be corrected with revision surgery. This corrective procedure is difficult, costly, and places the patient at an elevated risk for infection.

WHY MESS WITH SUCCESS?

When total joint arthroplasty was first put into practice the majority of the patients were elderly with limited mobility and low levels of activity. More times than not, the life of the implant exceeded that of the patient and, thus, fatigue failure of bone cement was not a pressing issue. However, today’s patients are hardly those of yesterday. Current candidates (which include the aging baby-boomer population) for total joint arthroplasty are younger, more active, living longer, and, in some cases, heavier.

According to the American Academy of Orthopaedic Surgeons (AAOS), the most popular total joint replacements are knees (~381,000 cases of primary surgery in 2002) and hips (~193,000 cases of primary surgery in 2002). These numbers will only increase as the baby boomers enter their golden years. As the number of primary surgical procedures increases so will the number of revision surgeries (if the current technology is not improved). AAOS revealed that in 2003 the cost of revision knee and hip surgeries in the United States reached $1.5 billion and $1.7 billion, respectively. Some prognosticators predict that the total cost of revision surgery will exceed $24 billion by the year 2030.

Although not all clinical failures of joint replacements are attributed to fatigue failure of the bone cement mantle, even slight improvements in its performance could have major implications for the healthcare system. Improving fatigue performance of bone cement is necessary for maximizing the clinical life of the implant as well as reducing healthcare expenditures.

A TINY SOLUTION TO A BIG PROBLEM

Many have tried to incorporate small amounts of various additive materials (especially fibers) into acrylic bone cement in hopes of improving the mechanical properties. Specifically, fibers of metal, ceramic, glass, polymer, and carbon have been added to bone cement to bridge incipient fatigue cracks and arrest or slow their propagation. For various reasons, including large fiber size and ductile fiber deformation, these efforts have yielded less than ideal results. Current reports on such composites are promising, but room for improvement exists.

The introduction of nanoscale materials, particularly carbon nanotubes, offers promise for augmenting the properties of polymer systems, including acrylic bone cement. Carbon nanotubes, in both single and multiwall varieties, have emerged as one of the most exciting, unique, and widely studied nanomaterials. Multiwall carbon nanotubes (MWNTs) are flexible and resilient tubular structures with diameters of 10 – 40 nanometers, lengths of 10 – 150 microns, and strength 50 - 100 times greater than steel at a fraction of the weight. Thus, it is believed that carbon nanotubes offer promise for improving the fatigue performance of acrylic bone cement, succeeding where other material augmentation efforts have failed.

MULTIWALL CARBON NANOTUBES IMPROVE FATIGUE PERFORMANCE

In 2001, a collaboration between the Center for Applied Energy Research, the Center for Biomedical Engineering, and the Department of Orthopaedic Surgery at the University of Kentucky spearheaded investigations of the potential benefits of adding multiwall carbon nanotubes to acrylic bone cement, especially as they pertain to fatigue performance. An experiment was designed to examine the effects of MWNT concentration (0 - 10 % by weight) and stress amplitude (20, 30, 35 MPa) on the fatigue performance of acrylic bone cement.

Figure 2. The number of cycles to failure of each sample was plotted as a function of MWNT concentration and stress amplitude. The optimal concentration of MWNTs appeared to be between 2% and 5% by weight. The positive effect of the MWNTs on fatigue performance diminished as the stress amplitude was increased. This was likely due to magnification of the negative effects of NWNT agglomerations at the higher stresses. It is likely that the effectiveness of MWNT reinforcement was also diminished. The estimated stress levels in the bone cement layer of a total hip arthroplasty are less than those studied here.
Disaggregating and dispersing the entangled as-produced MWNTs was paramount to the success of the composite material. Adequate dispersion was achieved with high temperature, shear mixing. The importance of dispersing the MWNTs cannot be overstated. Poorly disaggregated nanotubes behave similarly to voids in the bone cement and accelerate failure by negating the positive reinforcing effects of the well-dispersed MWNTs (Figure 1).

The MWNT – bone cement specimens were aged in heated (37°C) phosphate buffered saline (PBS) for a minimum of six days and each specimen was subsequently tested to failure in the physiologically-relevant environment.

The addition of multiwall carbon nanotubes improved the fatigue performance of acrylic bone cement by as much as 7 times (Figure 2). The results of the experiment revealed two things: first, the effect of the MWNTs was dose dependent (in other words, the fatigue performance greatly depended on the concentration of MWNTs) with the optimal concentration of MWNTs to be within the range of 2-5% by weight. Second, the stress amplitude of the fatigue test greatly affected the magnitude of the enhancement. The effectiveness of MWNT reinforcement diminished as the stress amplitude increased. This strongly suggests that the reinforcing capabilities of the MWNTs are maximized at lower stresses. A comparison to data in the literature revealed that the smallest stress amplitude in our study was much greater than stresses believed to be present in the in vivo bone cement layer.

To fully understand how the carbon nanotubes are positively affecting fatigue performance, it is important to understand what is happening to the microstructure of the bone cement as it fatigues. Despite the best efforts of surgeons worldwide, no bone cement mantle is flawless. Even the smallest flaw can have a major impact on fatigue performance. Pores, voids, and flaws are stress concentrators, which means that the effects of the applied stress are magnified around the flaw. In an effort to counteract this elevated local stress, the molecules of the polymer reorient themselves into the direction of the applied stress. This movement of the polymer chains generates heat, which accelerates fatigue failure.

Over time, the stress concentration and localized heating cause the bone cement matrix to permanently deform. The reorientation of the polymer chains leave voids in the bone cement, which grow into a series of micro-cracks. Growth and coalescence of the micro-cracks, albeit on a small scale, ultimately lead to the initiation of a fatigue crack.

The MWNTs were able to improve the fatigue performance of bone cement for several reasons. First, the MWNTs shielded the bone cement mantle by absorbing a large percentage of the energy associated with the fatigue test. This shielding effect enabled the bone cement matrix to withstand higher loads for longer periods without deforming permanently. Second, given the high on-axis thermal conductivity of the MWNTs (which rivals that of a diamond), it is likely that they negated some of the thermal effects generated from polymer chain movement by dissipating heat away from the regions of micro cracking. Third, the small size of the MWNTs made it possible for individual nanotubes to slow the formation and coalescence of micro-cracks on the sub-micron scale, an issue not addressed by macro scale fibers.

As the micro-cracks formed, individual MWNTs spanned the cracks forming bridges between the faces of the crack (Figure 3). As the bone cement was loaded, the MWNTs resisted the separation of the crack faces. Although it is unlikely that one carbon nanotube could provide enough resistance to slow the growth of the crack, it is likely that thousands of carbon nanotubes working in parallel greatly slowed the rate of crack growth. The cumulative effect of crack bridging was slower crack growth and increased fatigue life.

Although these findings suggest that the addition of multiwall carbon nanotubes is a promising solution to the problem of fatigue failure, additional investigations are needed before this new biomaterial is ready for clinical deployment. For example, a clinically-relevant method of mixing the MWNTs and bone cement needs to be developed (preferably one that retains the two-phase nature of bone cement). Additionally, eliminating agglomerations of MWNTs altogether could further enhance fatigue performance. Nonetheless, MWNTs provide bone cement with the reinforcement that few other additives can.

**IMPLICATIONS**

The future implications for MWNT – bone cement composites is quite clear. Enhanced fatigue performance can directly lead to improved longevity of the clinical life of the implant, which will reduce the risk for premature failure, limit the case numbers of revisions surgeries, and reduce healthcare expenditures. Most importantly, the patient’s quality of life will be maintained at a high level for a longer period of time. The current results also have implications for a number of structural, aerospace, and other medical applications, especially those that call for lightweight, high-performance materials.

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Bad Energy Policies of the 1990s: We are Still Feeling the Repercussions

Much of America’s historical (and current) energy policy has been (and remains), with apologies to Winston Churchill, “a calamity wrapped in a disaster shrouded in catastrophe.” Witness the current congressional biofuels mandate, based on the premise that turning our food into fuel is preferable to importing oil. This has transformed us from a country that cannot fuel itself to one that cannot feed itself, and is one of the factors driving up the price of food to its highest level in modern times. Has energy policy in this country always been this bad?

Well sort of.

The subject of bad energy policy is so bountiful, the challenge is to find a place to start. The impact of the repeal of the “Power Plant and Industrial Fuel Use Act” by Congress in 1987 is a good choice. Congress had passed this act in 1978, which restricted the use of natural gas to produce electricity. Repealing this act was, at first, a move to a more open market and overall a good policy—more competition and lower costs to the consumer. Unfortunately, this was not the case for long. Natural gas deregulation was part of what was soon to be a double edged sword. The shackles were taken off one energy source - natural gas - only to be put on another - coal - when the next administration took power in 1992. The new coal policies were not part of a public debate and congressional action, but rather an act of the executive branch through its regulatory power.

It was widely made known that no new coal fired power plants would be permitted under the Clinton-Gore administration, which believed gas was cleaner and produced less CO₂ than coal. The most aggressive anti-coal policies I have seen in 31 years of work in energy research were ushered in.

During the early years of the administration the amount of power generation added to the grid was relatively low as there was some slack in capacity. Also power plant plans had to be retooled for the new reality. A few coal plants that had progressed too far to stop, were commissioned. The massive build-out of gas-fired electric generation really started to gain traction in 1999, and it was staggering (Figure 1). More than 40 GW of capacity was added in 2001 and 60 GW in 2002, which is more than the capacity of Germany. We added the generating capacity of all of Europe based entirely on natural gas in about seven years.

There was one problem. There was not enough gas to support all the new demand. Domestic gas resources had been exaggerated and oversold by the industry. Gas reserves are classified by type, which consist of “Proved Reserves” or what we know we have; “Conventional Resources” or what we think we might find; and “Unconventional Resources,” what we dream we could produce if only we had the technology. These included gas from tight black shale, which has proven to be difficult to develop, expensive and dirty. The estimated gas reserves in 2000 from American Gas Association and Energy Information Administration sources were 2,500 trillion cubic feet of “Technically Recoverable” reserves, a combination of all three. This estimate also included Canada, which is at least technically, is not part of the U.S.

If the entire gas fired electric generating capacity was installed as projected in 2000, gas was to be consumed an annual rate of 32 Trillion cubic feet/year. At that time the total amount of proven U.S. reserves were 160 TCF. Thus, we would consume gas for electric production at a rate of what amounted to five years of total “known” reserves. Yet during the implementation of this policy, the amount of gas produced per well drill was dropping, as was the production from existing wells. We would have to import much of this gas, mostly from Canada, a fact known by the administration, as the projection of imported gas needs by the EIA in 2000 demonstrate. The combination of the Clinton-Gore administration’s anti-coal policies, combined with exaggerated gas reserves, set the stage for future economic shock as well as higher CO₂ emissions.

COSTS TO THE CONSUMER

The build out of all the new gas-based generation capacity has tripled the cost of natural gas to both residential and commercial consumers (Figure 2) and induced instability in pricing, which is to be expected from a commodity stretched thin. The average annual rate of increase for the residential gas customers from
1982 to 1999 was about 2.6%. Pricing for the commercial customer was almost flat during that time. From 2000 to 2006 the average increase in cost was 9.0% for both residential and commercial customers, of which 13.2% is accounted for in January, the peak of heating season.

Because of the price stability of gas before 2000, the actual dollar cost of this policy can be estimated with some degree of confidence. To do this I calculated the rate of increase, on a monthly basis, of gas prices as projected from pre-deregula-

**Figure 2. Cost of natural gas in dollars**

The cost of this policy to the American consumer has been staggering, with the residential consumers paying by my estimate and additional $133,678,483,000 or about $2,100 per customer for the period 2000-2007. The commercial customers have paid an additional $88,631,000,000 or $17,215 per customer over the same period. This approximate $220 billion price tag does not include the cost to build the plants or the higher cost of electricity from unstable gas pricing. We now have electric utilities competing with their own customers for energy resources and then passing on the added costs for gas-generated power back to them in their electric bill.

On top of this, we are now importing more gas than ever (Figure 3). The cost to our balance of payments is subject to the double multiplier of higher gas prices and lower currency valuations.

**Figure 3. Natural Gas Imports in MMcf per Month.**

### COSTS TO THE ENVIRONMENT

One of the ironies of this policy is that it not only robbed the residential customer and undermined the competitiveness of American manufacturing; it actually increased CO₂ emissions. Natural gas is a precious direct-use fuel. It can be used in the home with great efficiency. Modern natural gas furnaces and water heaters are up to 99% efficient. Their exhaust is so cool that plastic pipe is used to vent it. Cooking with gas is instant on and instant off.

The real shame is that most of the gas generators built were single cycle gas combustion turbine systems with low thermal efficiencies (energy value of electricity produced/value of heat of fuel used) in the range of 30% to 32%, rather than the more costly combined cycle systems (i.e. a gas combustion turbine combined with a steam turbine) with thermal efficiencies of up to 50%. A modern pulverized coal system with a supercritical boiler has thermal efficiencies of about 40% to 42%. Thus, using gas to generate electricity wastes 50% to 70% of its energy value compared to using it directly.

More energy is lost in transmission and less efficient electric appliances and water heating systems as well.

The number of residential gas customers added in 2002, 2003 and 2004 dropped dramatically, by 12% to 25% from historical trends due to lack of available gas. This was during one of the greatest housing construction booms in our history. By taking the gas out of our homes and factories and putting it in competition with coal in the electric cycle, we are using it much less efficiently and are actually producing more CO₂. An order of magnitude estimate of this can be made. By subtracting the natural gas consumed by the electric utilities from 2002 to 2006, from a 2001 baseline, the first year EIA tracked gas usage in power systems, and factoring the amount of energy wasted by using it in power generation, I calculated an overall additional CO₂ emission, of 100 to 200 million tons over a non-gas generation base case.

### LESSONS TO BE LEARNED

The problem with our energy policies is that they are not formulated with what efficiency guru Dr. Edward Demings referred to as “profound knowledge,” that is an actual understanding of the consequence of our actions. They are poorly thought through efforts at market manipulation often shaped for political reasons, or some vague environmental goal that cannot actually be affected. The role of government should be to set the standards and let the market work. Free markets will choose the least costly route which is also the most efficient, producing the least amount of CO₂.

What would have occurred without these anti-coal policies is hard to know. Some gas plants would have been built as they are needed for peak power and make sense in some locations. However, we would also have added newer, cleaner and more efficient coal plants operating on purely domestic resources. It is hard to imagine any government action that might have done more damage to our economy and security than the foolish and short sighted energy policies that held sway from 1992 to 2000.

The primary sources of data for this editorial are U.S. DOE’s Energy Information Agency, whose web site is www.eia.doe.gov. This data is available to the public. Some of the EIA data is current. Some is from 2000 and was part of an internal review of energy policy that was prepared by the Center for Applied Energy Research of the University of Kentucky.
Energizing Kentucky

Recognizing the increasingly important role of energy in Kentucky, four colleges and universities have joined forces in an innovative partnership between public and private institutions to stimulate the efforts of government, business and education leaders in creating a far-reaching and collaborative statewide energy policy. This comprehensive effort is entitled “Energizing Kentucky.”

On April 17th in the rotunda of Kentucky’s capitol in Frankfort, the presidents announced the “Energizing Kentucky” series of three conferences. For more information, go to: http://www.energizingkentucky.com/.

Kentucky Mine Mapping Awarded Best Online Service

The Kentucky Mine Mapping Information System (headed by John Hiett and administered through the CAER) received the Best of Kentucky technology award in the Best Online Services category at the Kentucky Digital Government Summit. Development of the information system began in May 2004 with a $1 million grant from the Mine Safety and Health Administration and continues with support from the U.S. Office of Surface Mining. The Internet site, http://minemaps.ky.gov, provides online digitized and georeferenced maps showing the location and extent of underground mines in Kentucky. The Kentucky Office of Mine Safety and Licensing has confirmed the presence of more than 30,000 abandoned mines in Kentucky and its collection of over 165,000 individual mine documents is the largest in the world.