Nanomaterials in Biotechnology

Richard W. Siegel
Materials Science and Engineering Department
School of Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180

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Richard W. Siegel
Robert W. Hunt Professor
Materials Science and Engineering Department
Rensselaer Polytechnic Institute

The past decade has seen an explosive growth worldwide in the synthesis and study of a wide range of nanostructured materials. A brief overview of this field, and its relationship to nanotechnology in general, will be presented with respect to possible applications in biotechnology. Results from our recent investigations of a variety of nanocomposites and cellular interactions with nanoscale ceramics will be presented, along with some considerations of novel future directions.

WTEC Panel Report on:

Nanostructure Science and Technology

R & D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices

Edited by
Richard W. Siegel, Evelyn Hu and M.C. Roco

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NATIONAL
NANOTECHNOLOGY
INITITATIVE

http://www.nano.gov/

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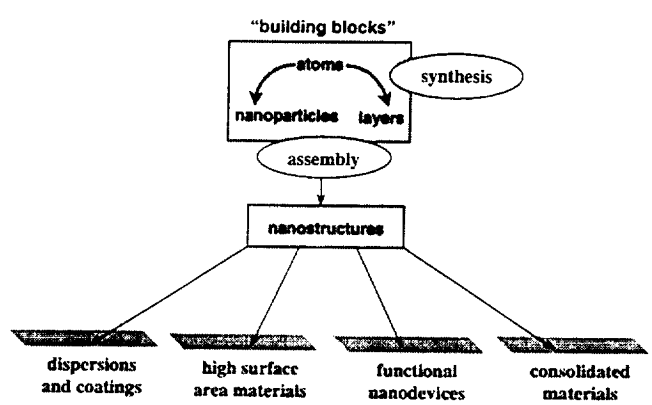
Nanotechnology Organization Chart



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Characteristics of Nanostructures
(Materials and Assemblies)

- ♦ Small
- ♦ Lightweight
- ♦ Novel properties
- ♦ Multifunctional
- ♦ Hierarchical
- ♦ Smart

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What Are Some Opportunities?

- ♦ Nanocomposite materials and coatings:
  - Thermal and environmental barriers
  - Wear resistant coatings and parts
  - Tailored optical and chemical barriers
  - Flame retardant plastics (packaging)
- ♦ High surface area nanostructures:
  - Fillers and catalysts
  - Energy storage media (batteries, fuel cells)
  - Drug or food supplement delivery vehicles

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♦ **Hierarchical Nanostructures**

- **Ultrahigh-strength, tough structural materials**
- **Ductile and strong cements**
- **Net-shape formed ceramic parts (wear, cutting)**
- **Magnetic/thermoelectric thermal management**
- **New materials for MEMS and sensors**
- **Smart materials with embedded sensors and actuators**

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The Ultimate Biomedical Goal of Nanotechnology:

"My idea is, we shrink a surgical team, inject it into a patient's vein, and then operate from the inside."

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Issues in Nanostructuring:

- ♦ Building Blocks
  - Scale
  - Composition
- ♦ Assembly
  - Interaction (interfaces)
  - Modulation dimensionality
  - Architecture (hierarchy)
- ♦ Function
  - Properties

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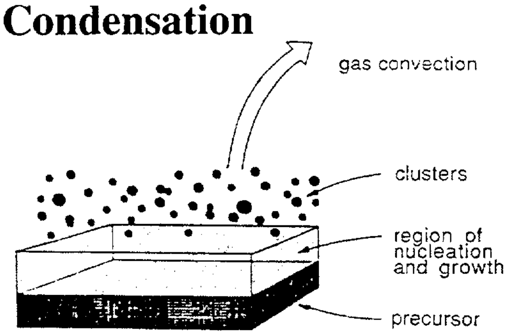
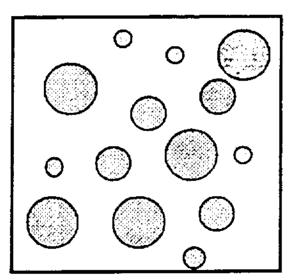
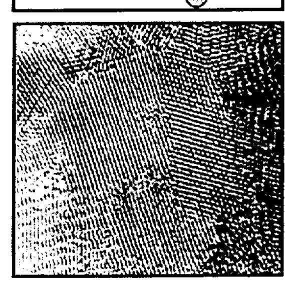
Cluster Synthesis by Gas Condensation







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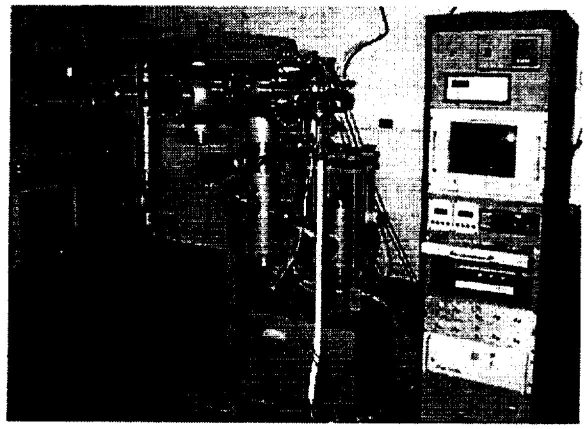
Nanoparticle Synthesis System at Rensselaer



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Nature:

Scaffold or template → fill with "nanoparticles"

Nanostructuring:

"Nanoparticle" building blocks → assembly

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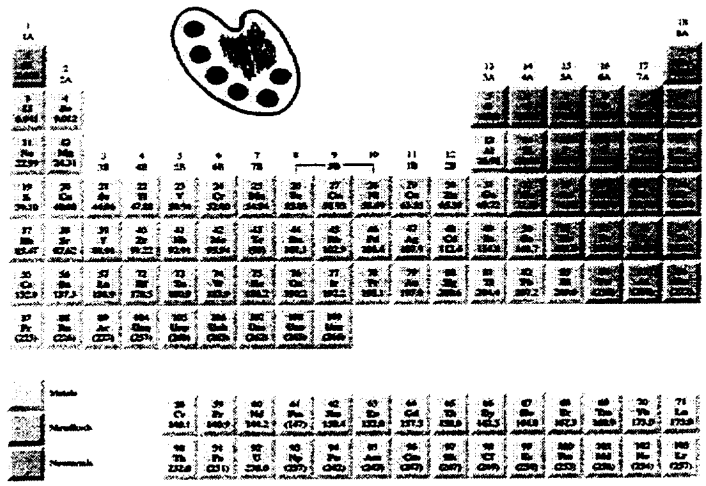
Palette for Nanostructuring



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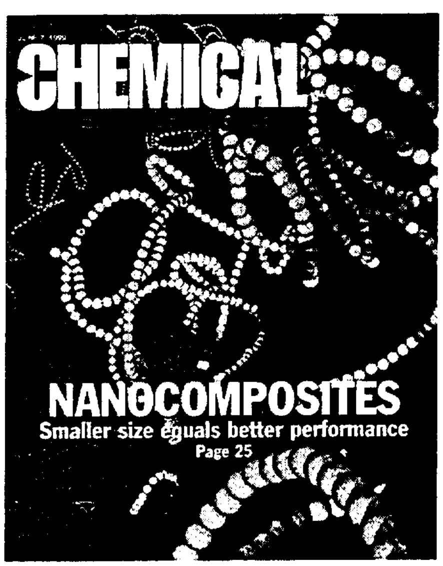

- matrix
- filler
- interface

Schadler, Ajayan et al. (1999)

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Nanocomposites: Opportunities

- **Fillers: Inorganic Nanoparticles, Carbon Nanotubes**
- **Matrices: Polymers, Ceramics**
  - **Large Interface Area**
  - **Light Weight**
  - **Variable Conductivity (Electrical, Thermal)**
  - **High Strength/Stiffness**
    - (Modulus of Nanotubes ~ 1 TPa)

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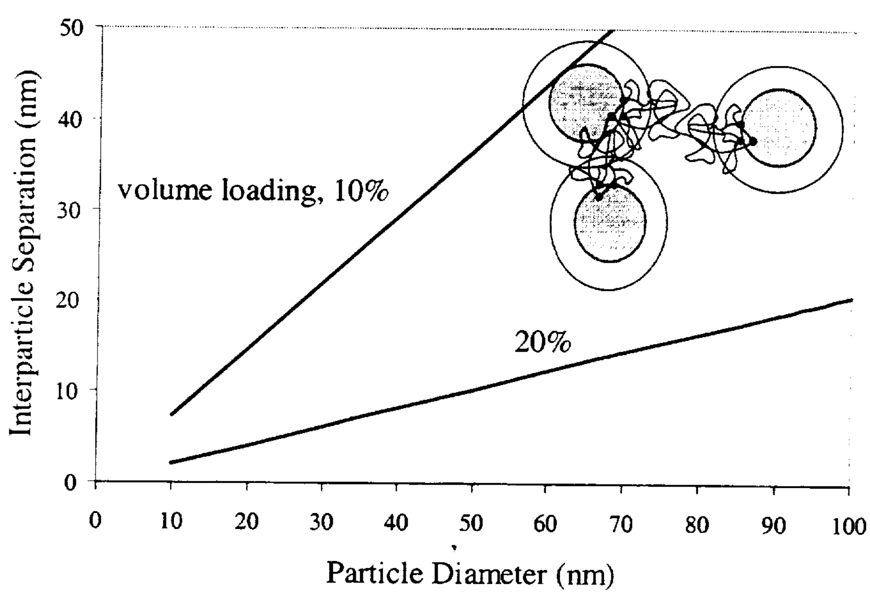

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Composite Systems Investigated

- Ceramic nanoparticles/polymer
- Carbon nanotubes/polymer
- Carbon nanotubes/nanophase ceramic

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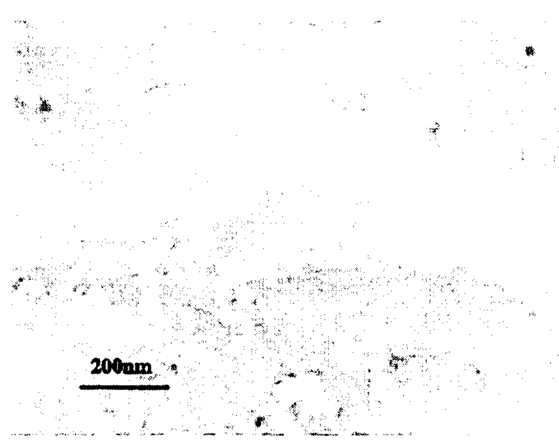
Titania/Epoxy Nanocomposite



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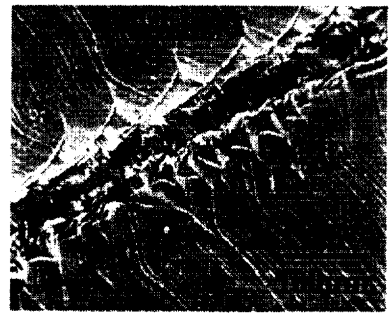
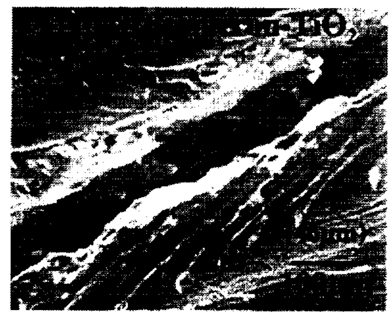
Scratch Testing

The damage surrounding the scratch is reduced for 10 wt% *nano*-TiO_2 filled epoxy, compared to 10 wt% micron-TiO_2 filled epoxy. (Scratch depth in parentheses.)





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Results of Tensile Testing

Materials	Modulus (GPa)	Strain to failure(%)
Epoxy	3.0	4.9 ± 0.9
5 wt% nano TiO_2/ Epoxy	3.4	N/A
10 wt% nano TiO_2/Epoxy	3.3	5.6 ± 0.9
10 wt% micron TiO_2/ Epoxy	3.3	4.1 ± 1.5
20 wt% nano TiO_2/Epoxy	3.5	3.0 ± 0.8

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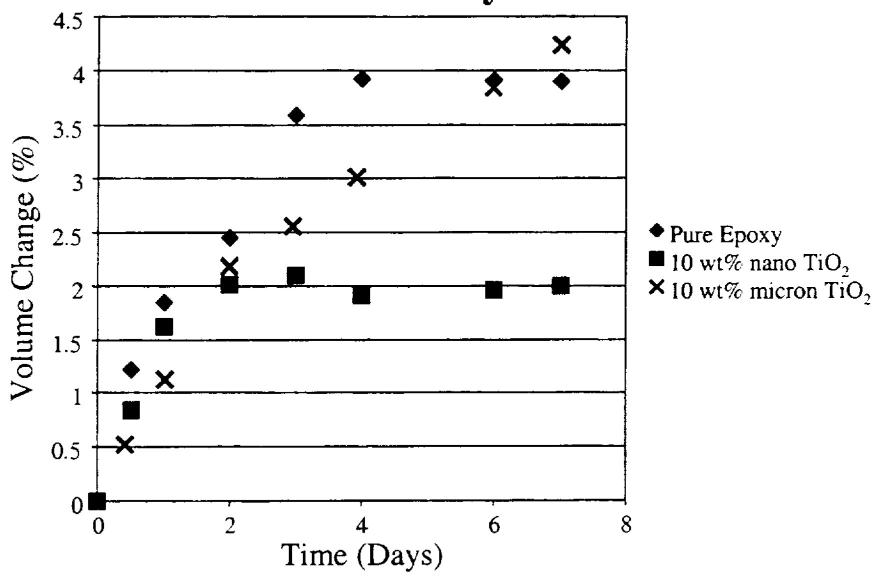
Dimensional Stability



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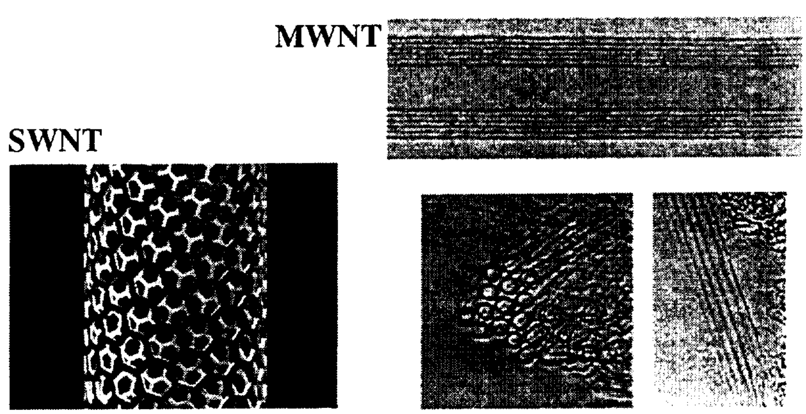
Carbon Nanotubes



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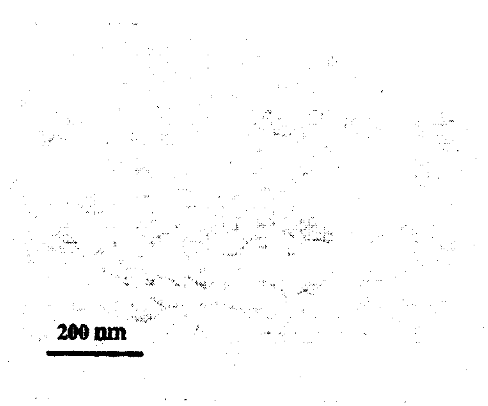
Carbon Nanotube/Alumina Nanocomposite



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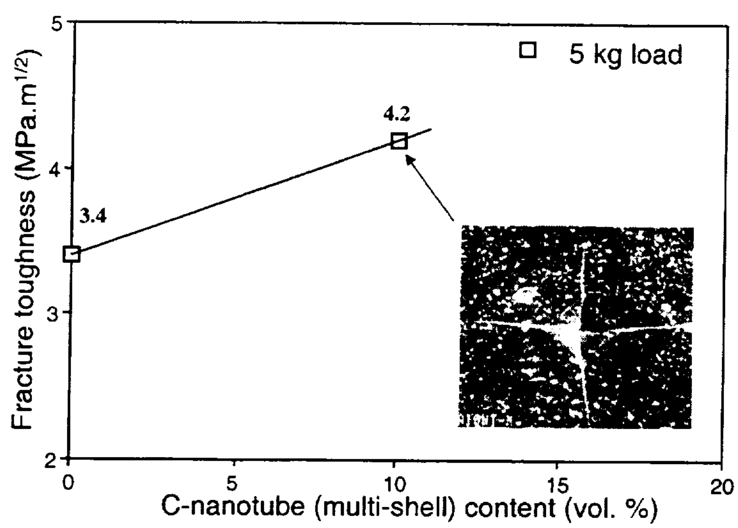
Fracture Toughness



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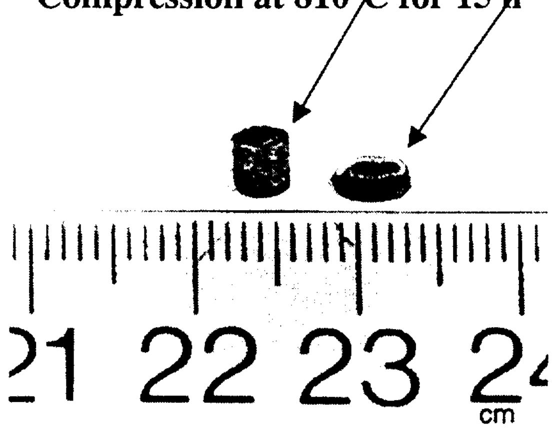
Nanophase TiO_2 Before and After Compression at 810°C for 15 h



Hahn et al. (1990)

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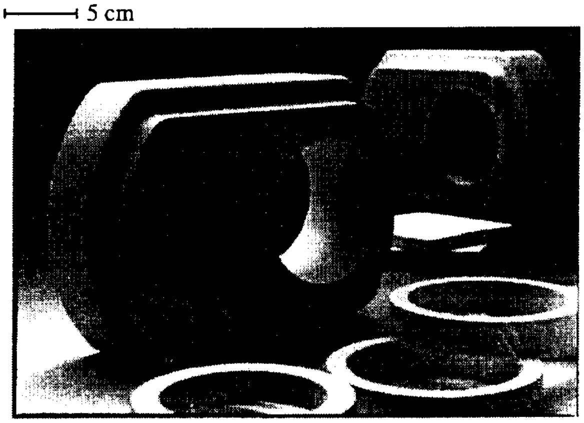
Net-shape Formed Ceramic (Al_2O_3) Parts

5 cm



Nanophase Technologies Corporation (1997)

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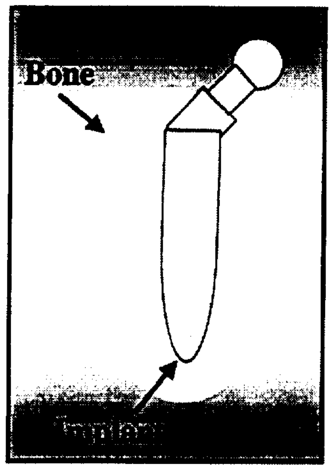
Consolidated Nanophase Ceramics as Biomaterials



Webster, Bizios et al. (2000)

- Formation and maintenance of viable bone closely apposed to the surface of biomaterials is essential for the clinical success of orthopaedic/dental implants.
- Insufficient bonding of juxtaposed bone to an implant could be caused by either surface properties that do not support new bone growth and/or mechanical properties that do not duplicate those of surrounding tissue.

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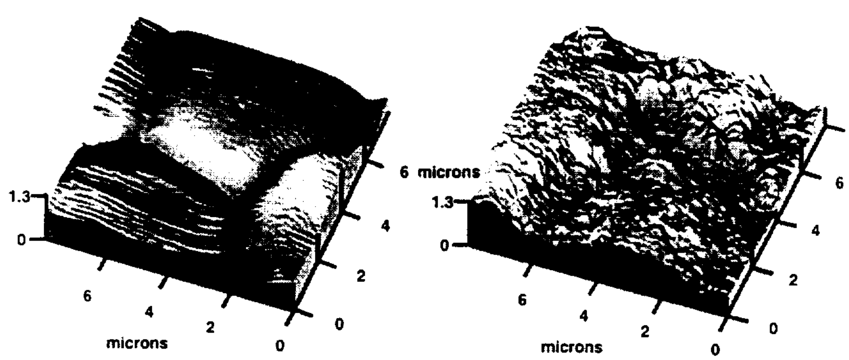
Atomic Force Micrographs of Nanophase and Conventional Titania



4.5 μm (conventional) Titania

39 nm (nanophase) Titania

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Bending Stiffness of Nanophase and Conventional Ceramics

Ceramic Grain Size (nm)		Bending Stiffness (GPa)
Alumina	24 (nanophase)	35.1 ± 2.8
	167 (conventional)	52.0 ± 6.8
Titania	39 (nanophase)	38.0 ± 7.6
	4,520 (conventional)	56.2 ± 8.9
Hydroxyapatite	67 (nanophase)	50.9 ± 4.5
	179 (conventional)	71.1 ± 8.2
Human Femur Bone		19.4 ± 2.4

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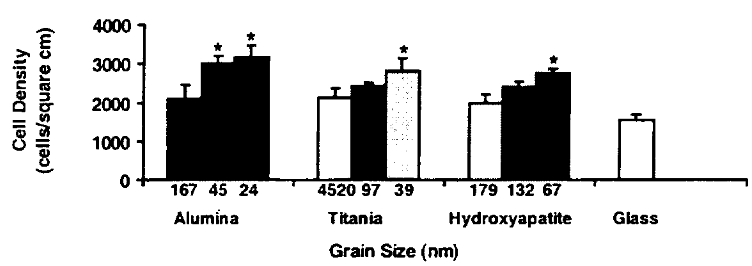
Enhanced Osteoblast Adhesion on Nanophase Ceramics



Culture media = DMEM supplemented with 10% fetal bovine serum. Adhesion time = 4 hours. Values are mean +/- SEM; n = 3; * $p < 0.01$ (student t-tests compared to respective conventional grain size ceramic).

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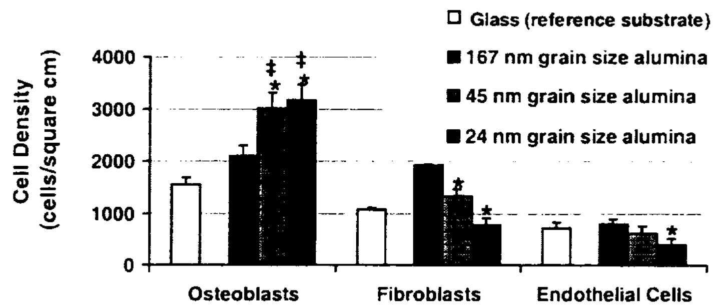
Comparison of Cell Adhesion on Nanophase Al_2O_3



Culture medium = DMEM supplemented with 10% fetal bovine serum. Adhesion time = 4 hours. Values are mean +/- SEM; n = 3; * $p < 0.01$ (student t-tests compared to 167 nm grain size alumina); ‡ $p < 0.01$ (student t-tests compared to fibroblast and endothelial cell adhesion on respective grain size alumina).

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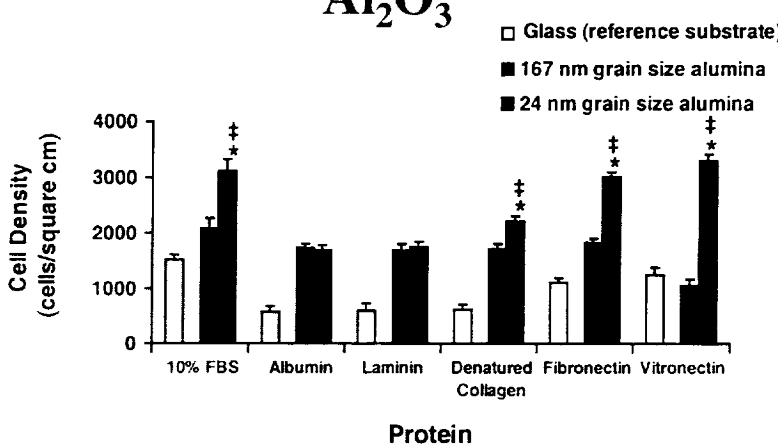
Osteoblast Adhesion on Nanophase Al_2O_3



Culture medium = DMEM without serum. Adhesion time = 4 hours. Values are mean +/- SEM; n = 3; * $p < 0.01$ (student t-tests compared to 167 nm grain size alumina); ‡ $p < 0.01$ (student t-tests compared to respective grain size alumina pretreated with albumin).

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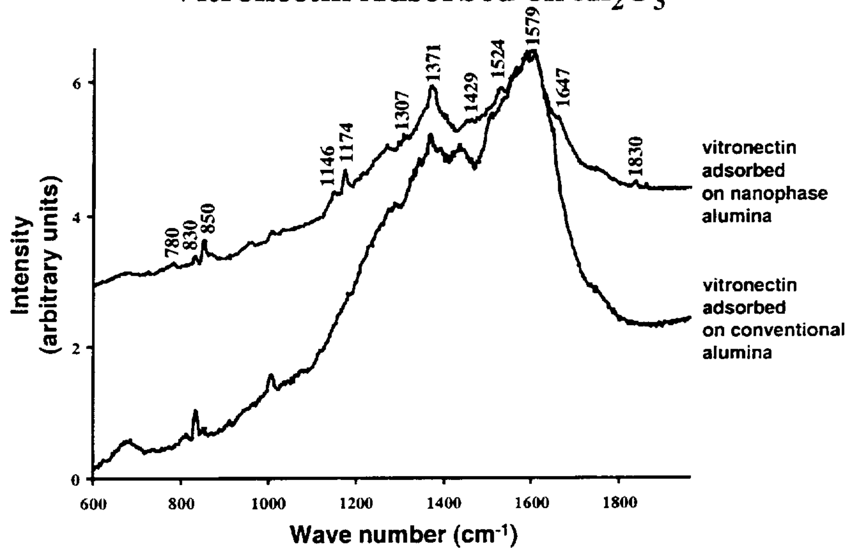
Surface Enhanced Raman Spectroscopy of Vitronectin Adsorbed on Al_2O_3



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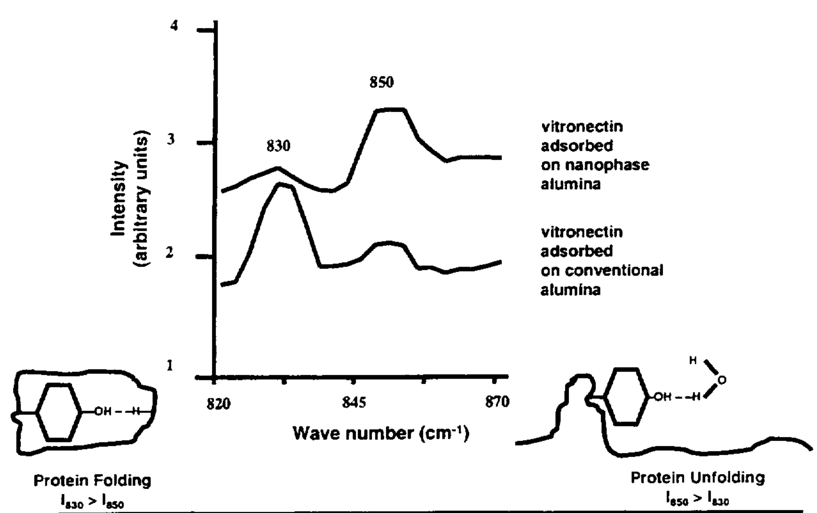
Tyrosine Doublet Ratio of Vitronectin Adsorbed on Alumina



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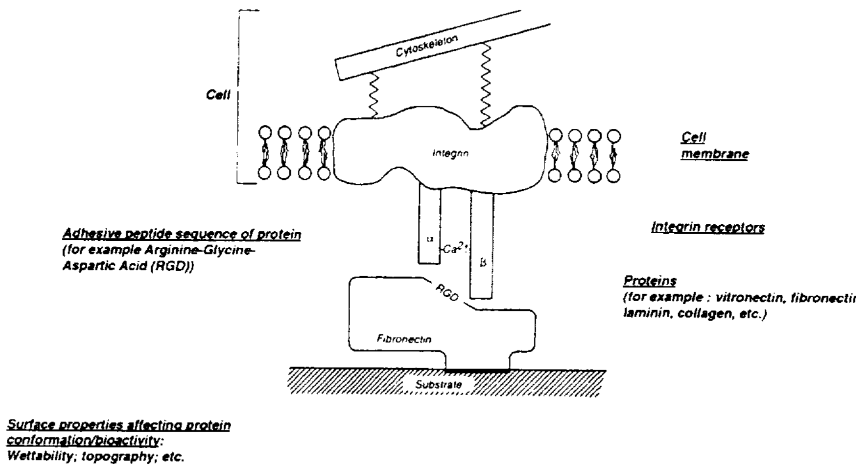
Cell-Biomaterial Interactions



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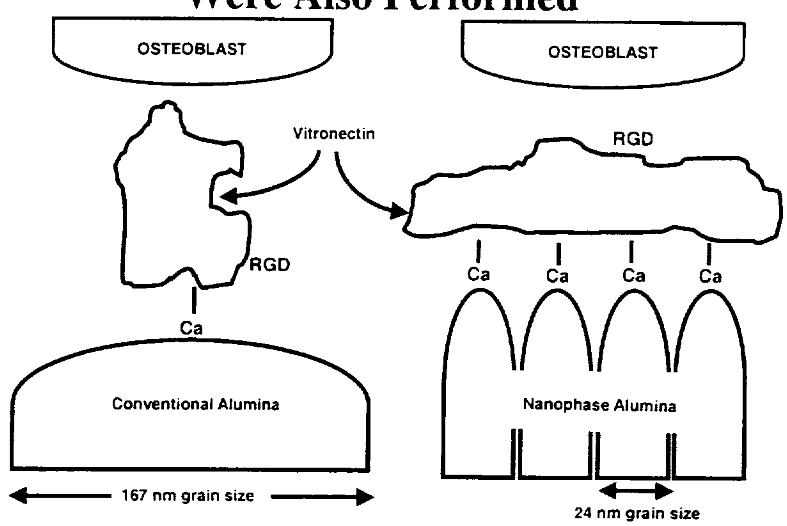
Competitive Inhibition Experiments Were Also Performed



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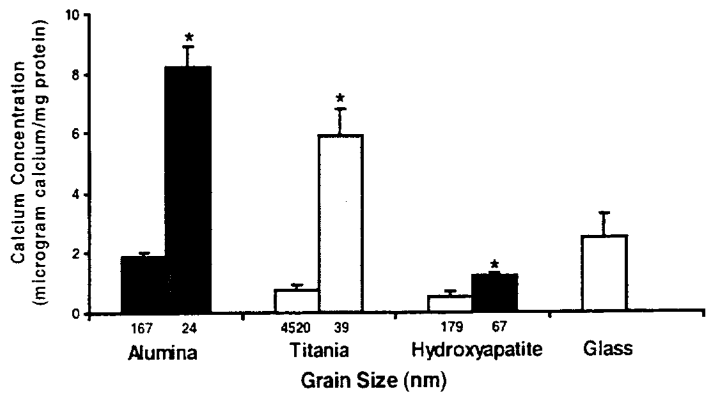
Enhanced Calcium Mineralization on Nanophase Ceramics



Culture medium = DMEM supplemented with 10% fetal bovine serum, 50 micrograms/mL L-ascorbate and 10 mM b-glycerophosphate. Culture time = 28 days. Values are mean +/- SEM; n = 3; * $p < 0.01$ (compared to respective conventional grain size ceramic).

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Bending Moduli of Nanophase and Conventional Alumina Composites with PLA

Bending Modulus (MPa)					
Pure PLA	Weight % alumina	30	40	50	100
324 ± 200	Nanophase	1,950 ± 510	977 ± 200	1,430 ± 800	3.7 ± 0.5
	Conventional	14.6 ± 2.0	1.7 ± 0.9	1.0 ± 0.7	2.6 ± 0.5

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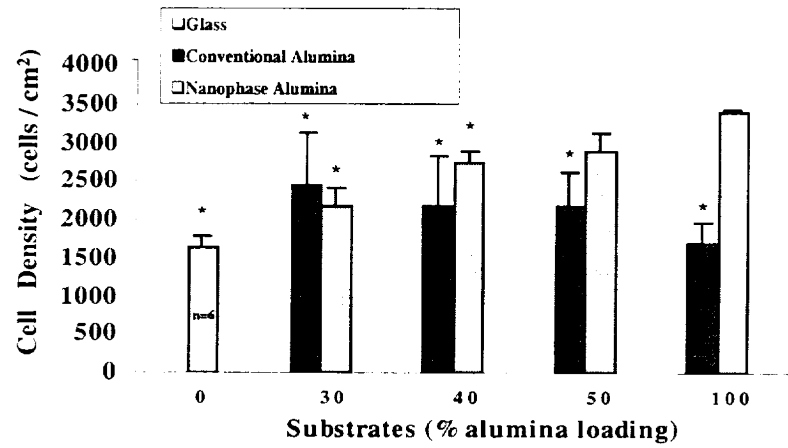
Osteoblast Adhesion on Nanophase Al_2O_3 and on Conventional Al_2O_3 Composites with PLA



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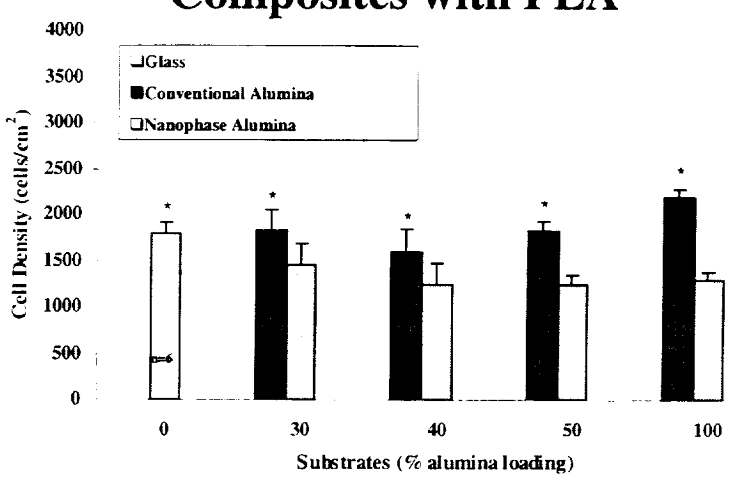
Fibroblast Adhesion on Nanophase Al_2O_3 and on Conventional Al_2O_3 Composites with PLA



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Technological Impact:
Present and Potential

Technology	Present	Potential
Dispersions and Coatings	♦ Thermal barriers ♦ Optical barriers (visible and UV) ♦ Imaging enhancement ♦ Ink-jet materials ♦ Coated abrasive slurries ♦ Information-recording layers	♦ Targeted drug delivery/gene therapy ♦ Multifunctional nano-coatings

Technological Impact
Present and Potential (Cont.)

Technology	Present	Potential
High Surface Area Materials	♦ Molecular sieves ♦ Drug delivery ♦ Tailored catalysts ♦ Absorption/ adsorption materials	♦ Molecule-specific sensors ♦ Large hydrocarbon or bacterial filters ♦ Energy storage ♦ Grätzel solar cells

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Technological Impact
Present and Potential (Cont.)

Technology	Present	Potential
Nanodevices	♦ GMR recording heads	♦ Terabit memory and microprocessing ♦ Single molecule DNA sizing and sequencing ♦ Biomedical sensors ♦ Low noise, low threshold lasers ♦ Nanotubes for high brightness displays

Technological Impact
Present and Potential (Cont.)

Technology	Present	Potential
Consolidated Materials	♦ Low-loss soft magnetic materials ♦ High hardness, tough WC/Co cutting tools ♦ Nanocomposite cements	♦ Superplastic forming of ceramics ♦ Ultra-high strength tough structural materials ♦ Magnetic refrigerants ♦ Nano-loaded polymer composites ♦ Ductile cements

Conclusion

Nanomaterials and nanotechnology will have an important and growing impact on biomedical applications in the coming years...

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