

Review Article

Carbon Nanotubes in Nanocomposites and Hybrids with Hydroxyapatite for Bone Replacements

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Hydroxyapatite (HA), as a bone mineral component, has been an attractive bioceramic for the reconstruction of hard tissues. However, its poor mechanical properties, including low fracture toughness and tensile strength, have been a significant challenge to the application of HA for the replacement of load-bearing and/or large bone defects. Among materials studied to reinforce HA, carbon nanotubes (CNTs: single-walled or multiwalled) have recently gained significant attention because of their unprecedented mechanical properties (high strength and toughness) and physicochemical properties (high surface area, electrical and thermal conductivity, and low weight). Here, we review recent studies of the organization of HA-CNTs at the nanoscale, with a particular emphasis on the functionalization of CNTs and their dispersion within an HA matrix and induction of HA mineralization. The organization of CNTs and HA implemented at the nanoscale can further be developed in the form of coatings, nanocomposites, and hybrid powders to enable potential applications in hard tissue reconstruction.

1. Introduction

Hydroxyapatite (HA; $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) has long been an attractive choice for bone replacement material [1–10]. With its similarity to the mineral component of natural bone, synthetic HA has shown excellent biocompatibility *in vitro* and *in vivo* [11]. However, HA has poor mechanical properties, such as brittleness and low tensile strength, thus the clinical applications have been limited particularly in load-bearing applications or large-sized defects [12].

One of the most common approaches to overcome this weakness is to produce composites by incorporating reinforcing phases, including strong bioceramics (ZrO_2 or Al_2O_3), tough metals (Ni_3Al), or flexible biopolymers (polyethylene and poly-lactide) [13–23]. These materials

have been shown to significantly affect the mechanical strength and/or toughness. Among the choices of reinforcing materials, carbon nanotubes (CNTs, including single-walled carbon nanotubes “SWCNTs” and multiwalled carbon nanotubes “MWCNTs”) have recently gained a great deal of attention [24–38]. This has mainly been due to the unprecedented mechanical properties of CNTs, such as stiffness and strength. These properties combined with the low density of CNTs indicate that they can potentially be used to reinforce HA for the development of strong and tough bone replacements. As well as the mechanical properties, CNTs also have unique properties from a structural, thermal, chemical, and electrical perspective [39–42]. Structurally, CNTs have a hollow geometry (diameter = 0.7–100 nm; length < several millimeters), large specific surface areas, and

high aspect ratios (length to diameter: about $1 \times 10^4 - 1 \times 10^6$). Moreover, due to the carbonaceous nature of the CNTs, they exhibit chemically and thermally high resistance that leads to the inhibition of oxidation by oxidative chemicals including oxygen [43–56].

Many researchers have attempted to apply CNTs as an organic phase for development of new CNT-assisted bone graft materials (HA-CNTs) in expectation of improved mechanical properties [24, 57–66] and bioactivity [67–69], respectively, because of the excellent mechanical properties of carbon nanotubes and the bioactivity of HA. Generally, the hybrid materials used for bone grafts should be osteoconductively designed to enable close integration with the surrounding bone tissue in the body. Therefore, in the case of HA-CNT nanohybrid material, HA layers formed on the surface of CNTs can be expected to provide excellent performance for complete harmony with natural bone tissue in the body since the bioactivity of HA-containing materials has been thoroughly demonstrated for dental and skeletal implants and bone-regenerative scaffolds [11].

While the applications of carbon nanotubes in human body have long been on debate due to their possible toxicity which is related to the nonbiodegradable nature [70, 71], many recent studies have started to elucidate the toxicity mechanism and to reduce toxicity by the functionalization or coating with organic and inorganic compounds that will improve their dispersibility in biological fluid [72]. For more information on the toxicity-related issues on CNTs, the readers may refer to some recent review articles [73].

In this paper, we aimed to focus on the works on HA-CNTs nanocomposites and hybrids developed for bone replacements. Several methodologies to prepare HA-CNT assembled bone graft materials such as mixing of CNTs with HA nanopowders to give rise to nanocomposites and the mineralization of HA directly on the surface of CNTs to produce hybrids have been summarized in terms of the functional groups existing on the CNTs.

2. Pristine CNTs and Conventional Composites

Pristine CNTs tend to agglomerate or form bundles due to the relatively strong π - π interaction between CNT molecules. Deagglomeration of these CNT agglomerates (or bundles) in water or organic solvents is still unsuccessful due to the persistent and high strength interaction. This problem becomes more acute when trying to disperse within solid matrices such as HA or metallic powders [74]. The high aspect ratio and stiffness of CNTs also account for the difficulty in homogeneous dispersion within matrix materials [74].

In terms of surface charge, HA powder and pristine CNTs are considered to be weakly negatively charged and/or neutral because there are a number of hydroxyl groups and π -electrons on the surface of HA crystals and CNT walls, respectively, (see Table 1 and the supplementary material available online at doi:10.4061/2011/674287) and it is this surface charge analogy between both components that could also be a primary reason for their poor homogenization. To

homogenize CNTs and HA, all experimental attempts can be generally categorized into the following two methodologies: CNT dispersion into HA matrices for the synthesis of HA-CNT composites (Table 2, entries 1–4) and HA mineralization onto CNT matrices for the synthesis of HA-CNT hybrids (Table 2, entry 5).

2.1. CNT Dispersion into HA Matrices (HA-CNT Composites). To disperse CNT powder throughout the HA matrix material, several physicochemical blending methods have been developed, including ball milling [74–77], mixing in solvent [78], and in situ formation of CNTs in HA matrix (see Table 2 and Figure 1) [79].

Chen et al. [74–76] made unfunctionalized CNT-reinforced HA composite through ball-milling. In the study, pristine CNTs in different weight proportions (0–20%) were first ball-milled together with HA powder before the composite was used in surface coating by laser surface alloying. When compared with the CNT-free HA coating, the hardness and modulus of the CNT-reinforced HA coating were improved by 42.7 and 20.6%, respectively. Balani et al. [77] introduced plasma spraying as a definitive tool to coat HA-CNT powder onto metallic implants while providing uniform distribution of unfunctionalized CNTs. To accomplish this, they mixed HA powder of 10–50 μm particle in size with 4 wt% CNTs in a jar mill for 18 h to obtain HA-CNT composite powder. After this they successfully coated the powder mixture onto Ti-6Al-4V bioimplant substrate by plasma spraying. They observed improvements in fracture toughness and crystallinity of 56 and 27%, respectively, and demonstrated the nontoxicity of the HA-CNT coating by cell culture study. Lu et al. [79] reported that HA-CNT nanocomposites (about 1 wt% CNT) can be fabricated by in situ formation of CNTs in HA matrix via chemical vapor deposition (CVD). According to the in situ technique, CNT growth took place on an alumina powder containing an iron catalyst.

2.2. HA Mineralization onto CNT Matrices (HA-CNT Hybrids). In fact, HA mineralization occurs in the body with the help of organic molecules for the formation and maintenance of bones and teeth. Therefore, the mineralization process can be appropriate to homogenize HA onto individual CNT molecules to form HA-CNT nanohybrids (see Figure 2). Since the first report of Abe et al. on the biomimetic HA mineralization in 1990 [80], several types of Ca-P precursor solutions including simulated body fluid (SBF) and Dulbecco's phosphate-buffered saline (DPBS) have been employed for the HA mineralization. The Ca-P solutions used for the HA mineralization are summarized in Table 3 [81–83].

Several researchers also employed unfunctionalized CNTs as HA mineralization-inducing nanotemplates, but the mineralization efficacy was usually poor. Moreover, low levels of HA crystal formation and thus large aggregates of CNTs occurred, leading to the formation of heterogeneous composite. However, most studies claimed that the tubular structure of CNTs provides more favorable morphology

TABLE 1: The Zeta (ζ) potential values of hydroxyapatite^a, SWCNT^b, and MWCNT^b powders.

Substrate	Particle size (nm)	Degree of purity (%)	Zeta (ζ) potential ^c (mV)
Hydroxyapatite	Diameter: hundreds of nanometers	>99	-2.4
SWCNT	Diameter: 1.3–1.5 nm Bundle diameter: 20–30 nm	60–70	-7.8
MWCNT	Diameter: 5–20 nm Length: 20 μ m	>95	-3.6

^a Purchased from Sigma Aldrich Korea and calcined at 900°C for 3 h; ^b Purchased from Hanwha Nanotech Co., Ltd. (Seoul, Korea); ^c Recorded using a Zetasizer nano ZS90 (Malvern) at room temperature and pH = 7.0.

TABLE 2: Synthesis procedures for production of HA-CNT composites and hybrids.

Entry	Blending method	CNT content	Mechanical properties
1	Ball-milling/laser-alloying [74–76]	<20 wt%	Hardness: increase up to 43% Modulus: increase up to 21%
2	Jar-milling/plasma spraying [77]	4 wt%	Toughness: increase up to 56%
3	^a In solvent mixing [78]	<20 wt%	Not measured
4	In situ synthesis via CVD [79]	1 wt%	Not measured
5	Mineralization [80–87]	^b Not measured	Not measured

^a See Section 4.1 for details.

TABLE 3: Type and chemical composition of Ca-P precursor solutions used for the HA mineralization onto CNTs.

Reagent	Type and chemical composition (mg/l) of Ca-P precursor solution			
	SBF-1	SBF-2	SBF-3	PBS
NaCl	7996	866	6547	8000
NaHCO ₃	350	—	2268	—
KCl	244	625	373	200
Na ₂ HPO ₄ ·2H ₂ O	—	—	178	1150
K ₂ HPO ₄	174	803	—	—
KH ₂ PO ₄	—	326	—	200
MgCl ₂ ·6H ₂ O	143	59	305	47
CaCl ₂ ·2H ₂ O	278	125	368	100
Na ₂ SO ₄	71	—	71	—
(CH ₂ OH) ₃ CNH ₂	6057	—	6057	—
NaF	22	22	—	22
pH	7.4	7.2	7.4	7.4

for the HA crystallization when compared to other carbon materials [84–86]. A study conducted by Akasaka et al. [84] revealed that the composition and concentration of Ca-P solutions significantly affected the amount of HA crystals formed on the CNTs as well as the size and morphology of crystals. When unmodified CNTs were immersed in SBF solution, only small amount of HA was mineralized on the CNT surface even after a couple of weeks. More concentrated CaP solution such as 2x SBF facilitated a higher level of HA mineralization within the same period. The results indicate that pristine CNTs retain a low level of capacity to mineralize HA on the surface, and this was mainly due to the low number of nucleation sites which thus limit nucleation and growth of HA crystals. In a different approach, Kealley et al. [85, 86] prepared a densely compressed HA-CNT

composite sheet via chemical precipitation of HA crystals from a calcium phosphate solution, using the chemicals Ca(NO₃)₂·4H₂O and (NH₄)₂HPO₄ followed by hot isostatic compression at 100 MPa and 900°C under Ar gas. They found some enhanced results with respect to the crystallization of HA. Liao et al. [87] employed some different types of experimental conditions such as bamboo-structured CNTs and a Ca-P solution consisting of 0.5 M CaCl₂ and 0.5 M H₃PO₄ (Ca/P = 1.66) as a nucleation template and a calcium phosphate precursor, respectively. They observed relatively unique spindle-shaped apatite crystals precipitated on the CNTs and also obtained carbonated HA-CNT nanohybrids after treatment of the as-prepared HA-CNT hybrid with a solution of Na₂CO₃ (molar ratio of CO₃²⁻ = PO₄³⁻ = 3) for 2 h.

In conclusion, if pristine CNTs were used, a homogenous assembling of CNTs within the HA matrix is highly difficult by means of either physical mixing or mineralization route. It is likely that the following problems were responsible for this: aggregation (or bundle formation) via the well-known π - π interactions between the delocalized electron systems of the CNT surface, the limited number of nucleation sites of pristine CNTs, and the similarity of the surface charge of HA and pristine CNTs. Therefore, to overcome these difficulties related to the intrinsic physicochemical properties of CNTs, chemical modification of CNTs is the key strategy.

3. Strategies for CNT Modification

The chemical modifications of CNTs developed to date are summarized in Table 4 and schematically demonstrated in Figure 3.

Among the methods used to modify the CNT surface, oxidative cutting of CNTs using strong oxidants and acidic media has generally been regarded as a useful tool [88–91]. During functionalization of CNTs by chemical oxidation,

TABLE 4: Methods of surface functionalization of CNTs.

Entry	Method	Functional group
1	Oxidative cutting [88–92]	CNT-COOH, -OH, and -C=O
2	Covalent modifications of the carboxylated CNTs [93, 94]	CNT-C(O)OR, -C(O)NR ₂
3	Covalent modification [95–98]	CNT-R
4	Organic compound-wrapping [99]	{CNTs} {R-C(O)OH, -NH ₃ ⁺ X ⁻ and -SO ₃ H}
5	Reductive charging [100, 101]	[CNTs] ⁻ M ⁺
6	Oxidative charging [100, 102]	[CNTs] ⁺ X ⁻
7	Electrophilic alkylation [78]	[CNT-R] ⁺ X ⁻

R = H or organic moieties; X = inorganic anions; M = metallic cations.

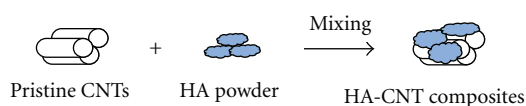


FIGURE 1: Schematic demonstration of the fabrication of HA-CNT composite powder by physicochemical blending methods.

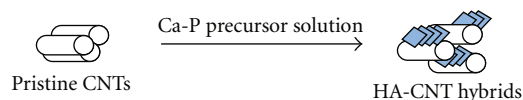


FIGURE 2: Schematic demonstration of HA mineralization onto pristine CNTs.

various functional groups such as -COOH, -OH, and -C=O were created on the surface of CNTs. The functional groups generally act as nucleation sites of metallic cations for their mineralization [92]. Moreover, to increase the interaction between CNTs and surrounding matrices (liquid or solid), additional modifications of the carboxyl groups introduced by the oxidative cutting have also been studied extensively [93, 94]. Generally, during the reaction procedure for the first oxidation and the further functionalization steps, nanotube bodies lose a proportion of their original properties and morphology. However, in terms of purification, the acid-treatment process has positive effects such as the effective removal of toxic metal impurities (such as catalyst residues) in CNT powder and amorphous carbon phases on CNT surface.

It has been shown that the use of highly reactive chemicals such as alkali metals and Brønsted super acids as reductants and oxidants, respectively, leads to charge separation on the outer walls of CNTs, resulting in positively or negatively charged CNT-derivatives bearing counter ions [100–102]. The charged CNT-derivatives generally were too unstable to be applied under aqueous and ambient conditions, because nanotube bodies were ionically changed too much.

To avoid serious damage to the nanotube body, solubilizers such as polycyclic aromatics, polymers, and various surfactants were employed to provide a relatively higher solubility [99]. However, the use of solubilizers in excess and the macromolecular behavior of solubilizer-CNTs micelles, which may occur through interactions between adjacent solubilizer-wrapped CNTs, have been found to prevent their

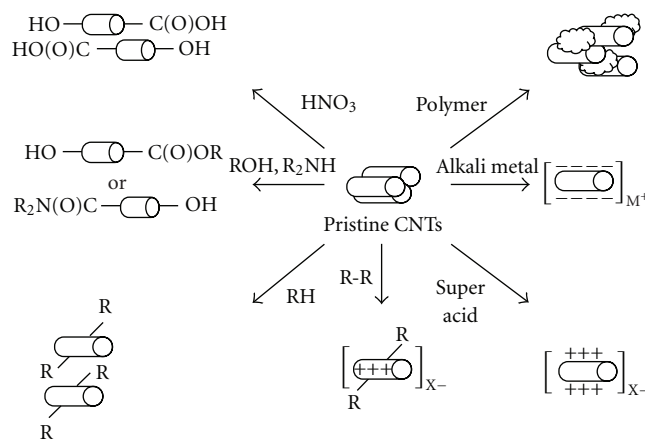


FIGURE 3: Schematic demonstration of CNT functionalization methods (R = H or organic moieties; X = inorganic anions; M = metallic cations).

use in appropriate applications. Moreover, the survival of CNT aggregates and the restricted scope of solvent types must still be addressed. Direct sidewall functionalization will be difficult because the reactivity of the sidewall is extremely low [95]. Indeed, attempts to covalently modify the sidewall have shown that it is a time-consuming method [96, 97]. For modification in large scale, this method has a weakness. A strategy to covalently and oxidatively modify the sidewall has been accomplished via Friedel-Crafts-type alkylation of CNTs with super acid-activated tetrahydrofuran (THF) as an electrophilic species, leading to the formation of positively charged sidewalls covalently bonded with butyl alcohol moieties (or their possible oligomers) and counter anions such as SbF₆⁻ and Cl⁻ [78]. Creating positive charges on outer walls may be useful in that it produces a bunch of nucleation sites for HA crystallization as well as those for ionic interaction with negatively charged HA powder.

4. Utilizing Modified CNTs for Nanocomposites and Hybrids

4.1. CNT Dispersion into HA Matrices (HA-CNT Nanocomposites)

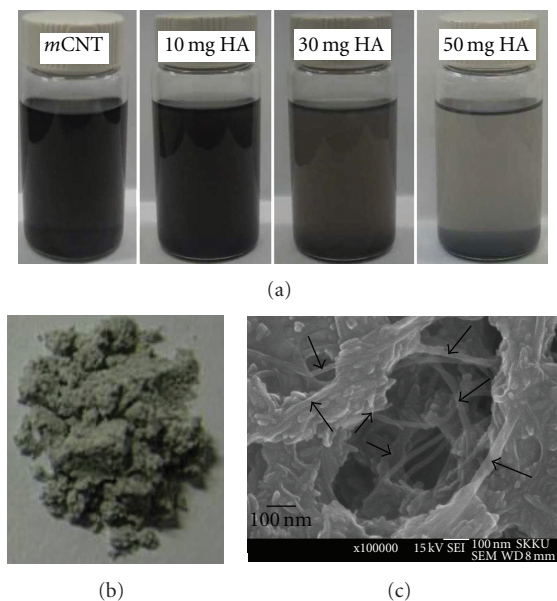


FIGURE 4: (a) Images showing the addition of negatively charged HA nanopowders to form precipitates with positively charged CNTs (*m*CNT) within THF solvent and (b) photographs and (c) high-resolution SEM morphology of the HA-CNTs composite nanopowders.

4.1.1. Use of Ionically Modified CNTs. As mentioned above, pristine CNTs have several limitations that prevent their homogenous distribution into HA powder matrices. When positive charges are introduced onto the outer walls of CNTs to combine with oppositely charged HA particles, the homogeneity of dispersion of the charged CNTs within the HA matrix might be easily achieved without a harsh physical blending process.

Our recent work [78] successfully prepared HA-CNT composite nanopowders in an organic solvent (see Figure 4). As a first step, the surface of the CNTs was positively modified, and then negatively charged HA nanopowders were added within the positively charged CNT derivative solution in an organic solvent (THF or ethanol), resulting in rapid precipitation of the composite HA-CNT nanopowders. The report also showed that the positively charged CNT powder could be combined in greater quantities with HA powder. High-resolution SEM revealed that individual CNTs were evenly distributed within the clusters of HA nanoparticulates.

4.2. HA Mineralization onto CNT Matrices (HA-CNT Hybrids). HA mineralization is a process that involves the controlled nucleation and growth of HA crystals from a confined Ca-P solution. When the CNTs surface was tailored with some ionic groups, either of the calcium or phosphate ions are guided on the surface which subsequently induces opposite charged ions to form nuclei which accompanies by clustering and crystallization and further crystal growth. Therefore, the initially functionalized groups should be well controlled in terms of their types of groups, interspacing

TABLE 5: HA mineralization on organic molecule-wrapped CNTs.

Modified CNTs	Ca-P solution	Reaction condition
SDS-wrapped CNTs [98]	Ca(NO ₃) ₂ , (NH ₄) ₂ HPO ₄	118°C, pH > 10
SDS-wrapped CNTs [103]	CaCl ₂ , Na ₂ HPO ₄	37.8°C, pH = 7.4
Citrate-wrapped CNTs [104]	CaCl ₂ , Na ₂ HPO ₄	37°C, pH = 7.4

distance and numbers, and so forth. Moreover, the ionic composition of the mineralization medium should also be importantly considered.

4.2.1. Use of Organic Molecule-Wrapped CNTs. As mentioned above, the simplest approach to functionalize CNT walls is wrapping the nanotubes with organic molecules such as surfactants and polymers. The noncovalent functionalization can allow the dispersion of CNTs in water while creating charged groups on the tube surfaces to provide nucleation sites. Several experiments of HA mineralization conducted on the organic molecule-wrapped CNTs are shown in Table 5.

Zhao and Gao reported the synthesis of HA-CNT composites using sodium dodecyl sulfate- (SDS-) treated CNTs and Ca(NO₃)₂ and (NH₄)₂HPO₄ solutions. The preparation process was conducted in an autoclave at 118°C and pH > 10, which resulted in the production of HA nanopowders containing 2 wt% CNTs [98]. Evaluation of the TEM images revealed that the HA nanoparticles were closely deposited on individually dispersed CNT molecules. Moreover, they found that the compressive strength of the CNT composite sintered at 1200°C was improved by about 61% from 63 to 102 MPa when compared with that of the single-phase HA hot-pressed at 1100°C. A similar procedure for mineralization using SDS-functionalized CNTs under different conditions was recently reported by Tan et al. [103]. They carried out the mineralization by dispersing the SDS-CNTs into an aqueous solution of CaCl₂ and Na₂HPO₄ at 37.8°C and pH = 7.4. TEM micrographs provided in the report showed that a needle-like HA mineral formed on the SDS decorated CNTs in relatively small quantity. Tasis et al. attempted CNT modification by citrate coating and mineralization in an aqueous solution of CaCl₂ and Na₂HPO₄ at 37°C and pH = 7.4 [104]. The mineralization was conducted on CNT buckypapers (CNT thin sheets) obtained after filtration of citrate-coated CNTs. They observed grain- and plate-like crystal images that were not evenly dispersed on the citrate-treated CNT material.

4.2.2. Use of Carboxylated CNTs. Before combining CNTs with HA, many studies of HA-CNT hybrids focused on the oxidative functionalization of CNTs to create hydrophilic functional groups such as -COOH, -OH, and -C=O. The number of the negatively charged functional groups created on the surface of CNTs during oxidative modifications is dependent on the reaction conditions such as oxidant type, reaction time, and temperature and also has a great effect on

TABLE 6: HA mineralization on carboxylated CNTs.

Modified CNTs	Ca-P solution	Reaction condition
CNT-C(O)OH	Ca(NO ₃) ₂ , (NH ₄) ₂ HPO ₄ [98, 105]	25 or 118°C, pH > 10
	SBF-3 in Table 3 [108]	37°C, pH = 7.4
	CaCl ₂ , Na ₂ HPO ₄ [107, 108]	25°C, in water

TABLE 7: Subsequent functionalization of the covalently derivatized CNTs for the HA mineralization [109].

Modified CNTs	Ca-P solution	Reaction condition
CNT-C(=O)OCH ₂ P(=O)(OEt) ₂	CaCl ₂ , Na ₂ HPO ₄	118°C, pH > 10
CNT-C(=O)NHC ₆ H ₄ CH ₂ P(=O)(OEt) ₂		
CNT-C(=O)NH(C ₆ H ₃ SO ₃ HNH) _n		
CNT-CONHC ₆ H ₄ CH ₂ P(=O)(OH) ₂		

the formation rate of the HA crystals, because, as previously mentioned, the functional groups can serve as calcium chelating sites to accelerate the growth of HA crystals. Studies of HA mineralization using carboxylated CNTs are briefly reviewed in Table 6.

Aryal et al. used carboxylated CNTs made in 60% nitric acid by reflux for 18 h at 110°C to prepare HA-CNTs with simulated body fluid (SBF-3 in Table 3) [106]. They found that the carboxylated CNTs effectively nucleated the HA crystals to form assemblies of HA and CNTs within 7 days. When they treated the CNT derivative with aqueous solutions of calcium chloride (0.01 M) and disodium hydrogen phosphate (0.01 M), multilayered plate-like assemblies with HA crystals were obtained [107, 108]. Recently, Pan et al. produced HA-CNT nanohybrids using carboxylated CNTs and Ca(NO₃)₂ and (NH₄)₂HPO₄ solutions by a one-step sonication process [105]. They dispersed the CNT derivatives into 0.1 M Ca(NO₃)₂ solution at pH = 10–12, and then 0.1 M (NH₄)₂HPO₄ solution was added dropwise at a rate of 2–4 ml/min with continuous sonication. They confirmed the formation of spindle-like HA nanoparticles with a width of 20–25 nm and a length of 50–100 nm bound to the functional groups of CNTs based on TEM images.

4.2.3. Covalently Further Treatment of the Carboxylated CNTs. The carboxylated CNTs were sometimes further functionalized with other chemical groups. The formation of amide and ester groups via the treatment of the carboxylated CNTs with amines and alcohols is one case (see Table 7) [94, 98].

Zhao et al. covalently transformed the carboxylated CNTs into a series of CNT derivatives bearing several functionalities including phosphonate groups such

as diethyl methylene phosphonate in ester form {CNT-C(=O)OCH₂P(=O)(OEt)₂}, diethyl benzyl phosphonate in amide form {CNT-C(=O)NHC₆H₄CH₂P(=O)(OEt)₂}, and the sulfonic acid group, poly(aminobenzene sulfonic acid) {CNT-C(=O)NH(C₆H₃SO₃HNH)_n} [109]. They investigated the efficacy of various functionalities on CNTs to attract calcium cation which leads to self-assembly of HA. To accomplish this, mineralization was conducted on a hydrophobic Teflon membrane using 10 mM CaCl₂ and 5 mM Na₂HPO₄ as mineral sources. High-resolution SEM images indicated that the phosphonate and sulfonate groups generally formed a large crystal-like HA bulk layer after only 1 day. To investigate the effect of the negative charges, they compared CNT-CONHC₆H₄CH₂P(=O)(OEt)₂ and the hydrolyzed form, CNT-CONHC₆H₄CH₂P(=O)(OH)₂; however, little difference in the effects of these compounds was observed. In the case of mineralization of CNT-C(=O)NH(C₆H₃SO₃HNH)_n, they claimed the formation of aligned plate-shaped HA crystals with a thickness of 3 μm after 14 days.

5. Conclusions

Because of the excellent properties of CNTs, such as mechanical strength and toughness, they are considered a promising reinforcing material for HA to find potential bone replacements. However, the major problem in the production of well-organized HA-CNTs nanocomposites and hybrids is the difficulty in homogenous distribution of pristine CNTs within the HA matrix. CNTs aggregation via the π - π interactions of the CNT surface and the lack of nucleation sites limit the dispersion of CNTs in HA nanopowders or the mineralization of HA crystals within ionic solutions. Therefore, functionalization of the CNTs surface with various methodologies has been popularly employed, which mainly include wrapping with surfactants or polymers and oxidation in harsh acidic conditions. Recent studies have shown some progress by activating the CNTs surface to have surface charges by an ionic-modification method. Using the modified CNTs, studies have shown a level of improvements in the dispersion status and/or the properties of the final composites. However, more studies need to be conducted in terms of the new modification techniques of the CNTs and addressing more well-controlled processes in composites or hybrids through the mineralization. This is because the exceptional properties of CNTs are still expected to provide a great opportunity to produce nanocomposites and hybrids with HA in the development of bone replacements.

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References

- [1] B. J. Melde and A. Stein, "Periodic macroporous hydroxyapatite-containing calcium phosphates," *Chemistry of Materials*, vol. 14, no. 8, pp. 3326–3331, 2002.
- [2] M. Takechi, Y. Miyamoto, K. Ishikawa et al., "Effects of added antibiotics on the basic properties of anti-washout-type fast-setting calcium phosphate cement," *Journal of Biomedical Materials Research*, vol. 39, no. 2, pp. 308–316, 1998.
- [3] A. Watson and D. Latchman, "Gene delivery into neuronal cells by calcium phosphate-mediated transfection," *Methods*, vol. 10, no. 3, pp. 289–291, 1996.
- [4] M. Stigter, K. De Groot, and P. Layrolle, "Incorporation of tobramycin into biomimetic hydroxyapatite coating on titanium," *Biomaterials*, vol. 23, no. 20, pp. 4143–4153, 2002.
- [5] D. Choi, K. G. Marra, and P. N. Kumta, "Chemical synthesis of hydroxyapatite/poly(ϵ -caprolactone) composites," *Materials Research Bulletin*, vol. 39, no. 3, pp. 417–432, 2004.
- [6] Y. C. Tsui, C. Doyle, and T. W. Clyne, "Plasma sprayed hydroxyapatite coatings on titanium substrates—part 1: mechanical properties and residual stress levels," *Biomaterials*, vol. 19, no. 22, pp. 2015–2029, 1998.
- [7] M. Hukovic, E. Tkalec, A. Kwokal, and J. Piljac, "An in vitro study of Ti and Ti-alloys coated with sol-gel derived hydroxyapatite coatings," *Surface and Coatings Technology*, vol. 165, no. 1, pp. 40–50, 2003.
- [8] D. Tadic, F. Peters, and M. Epple, "Continuous synthesis of amorphous carbonated apatites," *Biomaterials*, vol. 23, no. 12, pp. 2553–2559, 2002.
- [9] E. Banks, S. Nakajima, and L. C. Shapiro, "Fibrous apatite grown on modified collagen," *Science*, vol. 198, no. 4322, pp. 1164–1166, 1977.
- [10] S. Nam, J. E. Won, C. H. Kim, and H. W. Kim, "Odontogenic differentiation of human dental pulp stem cells stimulated by the calcium phosphate porous granules," *Journal of Tissue Engineering*, vol. 2011, Article ID 812547, 10 pages, 2011.
- [11] H. Liang, B. Shi, A. Fairchild, and T. Cale, "Applications of plasma coatings in artificial joints: an overview," *Vacuum*, vol. 73, no. 3-4, pp. 317–326, 2004.
- [12] A. J. Ruys, M. Wei, C. C. Sorrell, M. R. Dickson, A. Brandwood, and B. K. Milthorpe, "Sintering effects on the strength of hydroxyapatite," *Biomaterials*, vol. 16, no. 5, pp. 409–415, 1995.
- [13] W. Bonfield, M. D. Grynepas, A. E. Tully, J. Bowman, and J. Abram, "Hydroxyapatite reinforced polyethylene—a mechanically composite implant material for bone replacement," *Biomaterials*, vol. 2, no. 3, pp. 185–186, 1981.
- [14] J. H. Bradt, M. Mertig, A. Teresiak, and W. Pompe, "Biomimetic mineralization of collagen by combined fibril assembly and calcium phosphate formation," *Chemistry of Materials*, vol. 11, no. 10, pp. 2694–2701, 1999.
- [15] F. Miyaji, H. M. Kim, S. Handa, T. Kokubo, and T. Nakamura, "Bonelike apatite coating on organic polymers: novel nucleation process using sodium silicate solution," *Biomaterials*, vol. 20, no. 10, pp. 913–919, 1999.
- [16] N. Ignjatović, S. Tomić, M. Dakić, M. Miljković, M. Plavšić, and D. Uskoković, "Synthesis and properties of hydroxyapatite/poly-L-lactide composite biomaterials," *Biomaterials*, vol. 20, no. 9, pp. 809–816, 1999.
- [17] A. Bigi, E. Boanini, S. Panzavolta, and N. Roveri, "Biomimetic growth of hydroxyapatite on gelatin films doped with sodium polyacrylate," *Biomacromolecules*, vol. 1, no. 4, pp. 752–756, 2000.
- [18] J. D. Hartgerink, E. Beniash, and S. I. Stupp, "Self-assembly and mineralization of peptide-amphiphile nanofibers," *Science*, vol. 294, no. 5547, pp. 1684–1688, 2001.
- [19] M. Kikuchi, S. Itoh, S. Ichinose, K. Shinomiya, and J. Tanaka, "Self-organization mechanism in a bone-like hydroxyapatite/collagen nanocomposite synthesized in vitro and its biological reaction in vivo," *Biomaterials*, vol. 22, no. 13, pp. 1705–1711, 2001.
- [20] Y. Yang, J. L. Magnay, L. Cooling, and A. J. El Haj, "Development of a "mechano-active" scaffold for tissue engineering," *Biomaterials*, vol. 23, no. 10, pp. 2119–2126, 2002.
- [21] S. N. Park, J. C. Park, H. O. Kim, M. J. Song, and H. Suh, "Characterization of porous collagen/hyaluronic acid scaffold modified by 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide cross-linking," *Biomaterials*, vol. 23, no. 4, pp. 1205–1212, 2002.
- [22] E. I. Dorozhkina and S. V. Dorozhkin, "Surface mineralization of hydroxyapatite in modified simulated body fluid (mSBF) with higher amounts of hydrogencarbonate ions," *Colloids and Surfaces A*, vol. 210, no. 1, pp. 41–48, 2002.
- [23] W. Zhang, S. S. Liao, and F. Z. Cui, "Hierarchical self-assembly of nano-fibrils in mineralized collagen," *Chemistry of Materials*, vol. 15, no. 16, pp. 3221–3226, 2003.
- [24] A. Peigney, "Composite materials: tougher ceramics with nanotubes," *Nature Materials*, vol. 2, no. 1, pp. 15–16, 2003.
- [25] H.-H. Lee, U. S. Shin, G.-Z. Jin, and H.-W. Kim, "Highly homogeneous carbon nanotube-polycaprolactone composites with various and controllable concentrations of ionically modified-MWCNTs," *Bulletin of the Korean Chemical Society*, vol. 32, no. 1, pp. 157–161, 2011.
- [26] C. Balázs, Z. Kónya, F. Wéber, L. P. Biró, and P. Arató, "Preparation and characterization of carbon nanotube reinforced silicon nitride composites," *Materials Science and Engineering C*, vol. 23, no. 6-8, pp. 1133–1137, 2003.
- [27] Z. Xia, L. Riestler, W. A. Curtin et al., "Direct observation of toughening mechanisms in carbon nanotube ceramic matrix composites," *Acta Materialia*, vol. 52, no. 4, pp. 931–944, 2004.
- [28] W. A. Curtin and B. W. Sheldon, "CNT-reinforced ceramics and metals," *Materials Today*, vol. 7, no. 11, pp. 44–49, 2004.
- [29] A. Peigney, C. Laurent, E. Flahaut, and A. Rousset, "Carbon nanotubes in novel ceramic matrix nanocomposites," *Ceramics International*, vol. 26, no. 6, pp. 677–683, 2000.
- [30] X. Wang, N. P. Padture, and H. Tanaka, "Contact-damage-resistant ceramic/single-wall carbon nanotubes and ceramic/graphite composites," *Nature Materials*, vol. 3, no. 8, pp. 539–544, 2004.
- [31] A. Peigney, E. Flahaut, C. Laurent, F. Chastel, and A. Rousset, "Aligned carbon nanotubes in ceramic-matrix nanocomposites prepared by high-temperature extrusion," *Chemical Physics Letters*, vol. 352, no. 1-2, pp. 20–25, 2002.
- [32] J. W. An, D. H. You, and D. S. Lim, "Tribological properties of hot-pressed alumina-CNT composites," *Wear*, vol. 255, no. 1-6, pp. 677–681, 2003.
- [33] R. Z. Ma, J. Wu, B. Q. Wei, J. Liang, and D. H. Wu, "Processing and properties of carbon nanotubes-nano-SiC ceramic," *Journal of Materials Science*, vol. 33, no. 21, pp. 5243–5246, 1998.
- [34] G. D. Zhan, J. D. Kuntz, J. Wan, and A. K. Mukherjee, "Single-wall carbon nanotubes as attractive toughening agents in alumina-based nanocomposites," *Nature Materials*, vol. 2, no. 1, pp. 38–42, 2003.

- [35] G. Y. Li, P. M. Wang, and X. Zhao, "Mechanical behavior and microstructure of cement composites incorporating surface-treated multi-walled carbon nanotubes," *Carbon*, vol. 43, no. 6, pp. 1239–1245, 2005.
- [36] J. Chłopek, B. Czajkowska, B. Szaraniec, E. Frackowiak, K. Szostak, and F. Béguin, "In vitro studies of carbon nanotubes biocompatibility," *Carbon*, vol. 44, no. 6, pp. 1106–1111, 2006.
- [37] R. L. Price, M. C. Waid, K. M. Haberstroh, and T. J. Webster, "Selective bone cell adhesion on formulations containing carbon nanofibers," *Biomaterials*, vol. 24, no. 11, pp. 1877–1887, 2003.
- [38] L. P. Zanello, B. Zhao, H. Hu, and R. C. Haddon, "Bone cell proliferation on carbon nanotubes," *Nano Letters*, vol. 6, no. 3, pp. 562–567, 2006.
- [39] S. Iijima, "Helical microtubules of graphitic carbon," *Nature*, vol. 354, no. 6348, pp. 56–58, 1991.
- [40] P. M. Ajayan, "Nanotubes from Carbon," *Chemical Reviews*, vol. 99, no. 7, pp. 1787–1799, 1999.
- [41] M. Terrones, "Science and technology of the 21st Century: synthesis, properties, and applications of carbon nanotubes," *Annual Review of Materials Research*, vol. 33, pp. 419–501, 2003.
- [42] M. S. Dresselhaus, G. Dresselhaus, J. C. Charlier, and E. Hernández, "Electronic, thermal and mechanical properties of carbon nanotubes," *Philosophical Transactions of the Royal Society A*, vol. 362, no. 1823, pp. 2065–2098, 2004.
- [43] R. H. Baughman, A. A. Zakhidov, and W. A. De Heer, "Carbon nanotubes—the route toward applications," *Science*, vol. 297, no. 5582, pp. 787–792, 2002.
- [44] L. Lu, Y. Zhai, Y. Zhang, C. Ong, and S. Guo, "Reinforcement of hydrogenated carboxylated nitrile-butadiene rubber by multi-walled carbon nanotubes," *Applied Surface Science*, vol. 255, no. 5, pp. 2162–2166, 2008.
- [45] T. Seeger, G. De la Fuente, W. K. Maser, A. M. Benito, M. A. Callejas, and M. T. Martínez, "Evolution of multiwalled carbon-nanotube/SiO₂ composites via laser treatment," *Nanotechnology*, vol. 14, no. 2, pp. 184–187, 2003.
- [46] F. H. Gojny, J. Nastalczyk, Z. Roslaniec, and K. Schulte, "Surface modified multi-walled carbon nanotubes in CNT/epoxy-composites," *Chemical Physics Letters*, vol. 370, no. 5–6, pp. 820–824, 2003.
- [47] X. Zhang, T. Liu, T. V. Sreekumar et al., "Poly(vinyl alcohol)/SWNT composite film," *Nano Letters*, vol. 3, no. 9, pp. 1285–1288, 2003.
- [48] S. Kumar, T. D. Dang, F. E. Arnold et al., "Synthesis, structure, and properties of PBO/SWNT composites," *Macromolecules*, vol. 35, no. 24, pp. 9039–9043, 2002.
- [49] M. A. Correa-Duarte, N. Wagner, J. Rojas-Chapana, C. Morscheck, M. Thie, and M. Giersig, "Fabrication and biocompatibility of carbon nanotube-based 3D networks as scaffolds for cell seeding and growth," *Nano Letters*, vol. 4, no. 11, pp. 2233–2236, 2004.
- [50] S. F. Wang, L. Shen, W. D. Zhang, and Y. J. Tong, "Preparation and mechanical properties of chitosan/carbon nanotubes composites," *Biomacromolecules*, vol. 6, no. 6, pp. 3067–3072, 2005.
- [51] R. A. MacDonald, B. F. Laurenzi, G. Viswanathan, P. M. Ajayan, and J. P. Stegmann, "Collagen-carbon nanotube composite materials as scaffolds in tissue engineering," *Journal of Biomedical Materials Research - Part A*, vol. 74, no. 3, pp. 489–496, 2005.
- [52] X. Shi, J. L. Hudson, P. P. Spicer, J. M. Tour, R. Krishnamoorti, and A. G. Mikos, "Injectable nanocomposites of single-walled carbon nanotubes and biodegradable polymers for bone tissue engineering," *Biomacromolecules*, vol. 7, no. 7, pp. 2237–2242, 2006.
- [53] B. Sitharaman, X. Shi, L. A. Tran et al., "Injectable in situ cross-linkable nanocomposites of biodegradable polymers and carbon nanostructures for bone tissue engineering," *Journal of Biomaterials Science*, vol. 18, no. 6, pp. 655–671, 2007.
- [54] E. T. Thostenson, Z. Ren, and T. W. Chou, "Advances in the science and technology of carbon nanotubes and their composites: a review," *Composites Science and Technology*, vol. 61, no. 13, pp. 1899–1912, 2001.
- [55] H. Dai, "Carbon nanotubes: opportunities and challenges," *Surface Science*, vol. 500, no. 1–3, pp. 218–241, 2002.
- [56] F. Lupo, R. Kamalakaran, C. Scheu, N. Grobert, and M. Rühle, "Microstructural investigations on zirconium oxide-carbon nanotube composites synthesized by hydrothermal crystallization," *Carbon*, vol. 42, no. 10, pp. 1995–1999, 2004.
- [57] C. Balázs, Z. Kónya, F. Wéber, L. P. Biró, and P. Arató, "Preparation and characterization of carbon nanotube reinforced silicon nitride composites," *Materials Science and Engineering C*, vol. 23, no. 6–8, pp. 1133–1137, 2003.
- [58] Z. Xia, L. Riestler, W. A. Curtin et al., "Direct observation of toughening mechanisms in carbon nanotube ceramic matrix composites," *Acta Materialia*, vol. 52, no. 4, pp. 931–944, 2004.
- [59] W. A. Curtin and B. W. Sheldon, "CNT-reinforced ceramics and metals," *Materials Today*, vol. 7, no. 11, pp. 44–49, 2004.
- [60] A. Peigney, C. Laurent, E. Flahaut, and A. Rousset, "Carbon nanotubes in novel ceramic matrix nanocomposites," *Ceramics International*, vol. 26, no. 6, pp. 677–683, 2000.
- [61] X. Wang, N. P. Padture, and H. Tanaka, "Contact-damage-resistant ceramic/single-wall carbon nanotubes and ceramic/graphite composites," *Nature Materials*, vol. 3, no. 8, pp. 539–544, 2004.
- [62] A. Peigney, E. Flahaut, C. Laurent, F. Chastel, and A. Rousset, "Aligned carbon nanotubes in ceramic-matrix nanocomposites prepared by high-temperature extrusion," *Chemical Physics Letters*, vol. 352, no. 1–2, pp. 20–25, 2002.
- [63] J. W. An, D. H. You, and D. S. Lim, "Tribological properties of hot-pressed alumina-CNT composites," *Wear*, vol. 255, no. 1–6, pp. 677–681, 2003.
- [64] R. Z. Ma, J. Wu, B. Q. Wei, J. Liang, and D. H. Wu, "Processing and properties of carbon nanotubes-nano-SiC ceramic," *Journal of Materials Science*, vol. 33, no. 21, pp. 5243–5246, 1998.
- [65] G. D. Zhan, J. D. Kuntz, J. Wan, and A. K. Mukherjee, "Single-wall carbon nanotubes as attractive toughening agents in alumina-based nanocomposites," *Nature Materials*, vol. 2, no. 1, pp. 38–42, 2003.
- [66] G. Y. Li, P. M. Wang, and X. Zhao, "Mechanical behavior and microstructure of cement composites incorporating surface-treated multi-walled carbon nanotubes," *Carbon*, vol. 43, no. 6, pp. 1239–1245, 2005.
- [67] J. Chłopek, B. Czajkowska, B. Szaraniec, E. Frackowiak, K. Szostak, and F. Béguin, "In vitro studies of carbon nanotubes biocompatibility," *Carbon*, vol. 44, no. 6, pp. 1106–1111, 2006.
- [68] R. L. Price, M. C. Waid, K. M. Haberstroh, and T. J. Webster, "Selective bone cell adhesion on formulations containing

- carbon nanofibers," *Biomaterials*, vol. 24, no. 11, pp. 1877–1887, 2003.
- [69] L. P. Zanello, B. Zhao, H. Hu, and R. C. Haddon, "Bone cell proliferation on carbon nanotubes," *Nano Letters*, vol. 6, no. 3, pp. 562–567, 2006.
- [70] A. Takagi, A. Hirose, T. Nishimura et al., "Induction of mesothelioma in p53+/- mouse by intraperitoneal application of multi-wall carbon nanotube," *Journal of Toxicological Sciences*, vol. 33, no. 1, pp. 105–116, 2008.
- [71] C. A. Poland, R. Duffin, I. Kinloch et al., "Carbon nanotubes introduced into the abdominal cavity of mice show asbestos-like pathogenicity in a pilot study," *Nature Nanotechnology*, vol. 3, no. 7, pp. 423–428, 2008.
- [72] L. Lacerda, A. Soundararajan, R. Singh et al., "Dynamic imaging of functionalized multi-walled carbon nanotube systemic circulation and urinary excretion," *Advanced Materials*, vol. 20, no. 2, pp. 225–230, 2008.
- [73] B. S. Harrison and A. Atala, "Carbon nanotube applications for tissue engineering," *Biomaterials*, vol. 28, no. 2, pp. 344–353, 2007.
- [74] Y. Chen, C. Gan, T. Zhang, G. Yu, P. Bai, and A. Kaplan, "Laser-surface-alloyed carbon nanotubes reinforced hydroxyapatite composite coatings," *Applied Physics Letters*, vol. 86, no. 25, Article ID 251905, pp. 1–3, 2005.
- [75] Y. Chen, Y. Q. Zhang, T. H. Zhang, C. H. Gan, C. Y. Zheng, and G. Yu, "Carbon nanotube reinforced hydroxyapatite composite coatings produced through laser surface alloying," *Carbon*, vol. 44, no. 1, pp. 37–45, 2006.
- [76] Y. Chen, T. H. Zhang, C. H. Gan, and G. Yu, "Wear studies of hydroxyapatite composite coating reinforced by carbon nanotubes," *Carbon*, vol. 45, no. 5, pp. 998–1004, 2007.
- [77] K. Balani, R. Anderson, T. Laha et al., "Plasma-sprayed carbon nanotube reinforced hydroxyapatite coatings and their interaction with human osteoblasts in vitro," *Biomaterials*, vol. 28, no. 4, pp. 618–624, 2007.
- [78] H. Y. Lee, U. S. Shin, J.-E. Won, and H.-W. Kim, "Preparation of hydroxyapatite-carbon nanotube composite nanopowders," *Materials Letters*, vol. 65, no. 2, pp. 208–211, 2011.
- [79] X. Lu, H. Wang, S. Xia, J. Wang, and J. Weng, "In situ growth of carbon nanotubes in hydroxyapatite matrix by chemical vapor deposition," *Advanced Materials Research*, vol. 79–82, pp. 1671–1674, 2009.
- [80] W. H. Song, Y. K. Jun, Y. Han, and S. H. Hong, "Biomimetic apatite coatings on micro-arc oxidized titania," *Biomaterials*, vol. 25, no. 17, pp. 3341–3349, 2004.
- [81] T. Akasaka, F. Watari, Y. Sato, and K. Tohji, "Apatite formation on carbon nanotubes," *Materials Science and Engineering C*, vol. 26, no. 4, pp. 675–678, 2006.
- [82] C. Kealley, M. Elcombe, A. van Riessen, and B. Ben-Nissan, "Development of carbon nanotube-reinforced hydroxyapatite bioceramics," *Physica B*, vol. 385–386, pp. 496–498, 2006.
- [83] C. Kealley, M. Elcombe, A. Van Riessen, and B. Ben-Nissan, "Neutron characterisation of hydroxyapatite bioceramics," *Key Engineering Materials*, vol. 309–311, pp. 61–64, 2006.
- [84] Y. Abe, T. Kokubo, and T. Yamamuro, "Apatite coating on ceramics, metals and polymers utilizing a biological process," *Journal of Materials Science*, vol. 1, no. 4, pp. 233–238, 1990.
- [85] H. M. Kim, T. Miyazaki, T. Kokubo, and T. Nakamura, "Revised simulated body fluid," *Key Engineering Materials*, vol. 192–195, pp. 47–50, 2001.
- [86] A. Oyane, M. Kawashita, K. Nakanishi et al., "Bonelike apatite formation on ethylene-vinyl alcohol copolymer modified with silane coupling agent and calcium silicate solutions," *Biomaterials*, vol. 24, no. 10, pp. 1729–1735, 2003.
- [87] S. Liao, G. Xu, W. Wang et al., "Self-assembly of nano-hydroxyapatite on multi-walled carbon nanotubes," *Acta Biomaterialia*, vol. 3, no. 5, pp. 669–675, 2007.
- [88] J. Liu, A. G. Rinzler, H. Dai et al., "Fullerene pipes," *Science*, vol. 280, no. 5367, pp. 1253–1256, 1998.
- [89] N. I. Kovtyukhova, T. E. Mallouk, L. Pan, and E. C. Dickey, "Individual single-walled nanotubes and hydrogels made by oxidative exfoliation of carbon nanotube ropes," *Journal of the American Chemical Society*, vol. 125, no. 32, pp. 9761–9769, 2003.
- [90] S. Ramesh, L. M. Ericson, V. A. Davis et al., "Dissolution of pristine single walled carbon nanotubes in superacids by direct protonation," *Journal of Physical Chemistry B*, vol. 108, no. 26, pp. 8794–8798, 2004.
- [91] Y. Wang, Z. Iqbal, and S. Mitra, "Rapidly functionalized, water-dispersed carbon nanotubes at high concentration," *Journal of the American Chemical Society*, vol. 128, no. 1, pp. 95–99, 2006.
- [92] Z. J. Liu, Z. Xu, Z. Y. Yuan, W. Chen, W. Zhou, and L. M. Peng, "A simple method for coating carbon nanotubes with Co-B amorphous alloy," *Materials Letters*, vol. 57, no. 7, pp. 1339–1344, 2003.
- [93] J. Chen, M. A. Hamon, H. Hu et al., "Solution properties of single-walled carbon nanotubes," *Science*, vol. 282, no. 5386, pp. 95–98, 1998.
- [94] B. Yu, F. Zhou, G. Liu, Y. Liang, W. T. S. Huck, and W. Liu, "The electrolyte switchable solubility of multi-walled carbon nanotube/ionic liquid (MWCNT/IL) hybrids," *Chemical Communications*, no. 22, pp. 2356–2358, 2006.
- [95] J. I. Aihara, "Lack of superaromaticity in carbon nanotubes," *Journal of Physical Chemistry*, vol. 98, no. 39, pp. 9773–9776, 1994.
- [96] J. L. Bahr, J. Yang, D. V. Kosynkin, M. J. Bronikowski, R. E. Smalley, and J. M. Tour, "Functionalization of carbon nanotubes by electrochemical reduction of aryl diazonium salts: a bucky paper electrode," *Journal of the American Chemical Society*, vol. 123, no. 27, pp. 6536–6542, 2001.
- [97] E. T. Mickelson, C. B. Huffman, A. G. Rinzler, R. E. Smalley, R. H. Hauge, and J. L. Margrave, "Fluorination of single-wall carbon nanotubes," *Chemical Physics Letters*, vol. 296, no. 1–2, pp. 188–194, 1998.
- [98] L. Zhao and L. Gao, "Novel in situ synthesis of MWNTs-hydroxyapatite composites," *Carbon*, vol. 42, no. 2, pp. 423–426, 2004.
- [99] A. Ishibashi and N. Nakashima, "Individual dissolution of single-walled carbon nanotubes in aqueous solutions of steroid or sugar compounds and their Raman and near-IR spectral properties," *Chemistry*, vol. 12, pp. 7595–7602, 2006.
- [100] A. M. Rao, P. C. Eklund, S. Bandow, A. Thess, and R. E. Smalley, "Evidence for charge transfer in doped carbon nanotube bundles from raman scattering," *Nature*, vol. 388, no. 6639, pp. 257–259, 1997.
- [101] A. Pénicaud, P. Poulin, A. Derré, E. Anglaret, and P. Petit, "Spontaneous dissolution of a single-wall carbon nanotube salt," *Journal of the American Chemical Society*, vol. 127, no. 1, pp. 8–9, 2005.
- [102] C. M. Liu, H. B. Cao, Y. P. Li, H. B. Xu, and Y. Zhang, "The effect of electrolytic oxidation on the electrochemical properties of multi-walled carbon nanotubes," *Carbon*, vol. 44, no. 14, pp. 2919–2924, 2006.
- [103] Q. Tan, K. Zhang, S. Gu, and J. Ren, "Mineralization of surfactant functionalized multi-walled carbon nanotubes

- (MWNTs) to prepare hydroxyapatite/MWNTs nanohybrid,” *Applied Surface Science*, vol. 255, no. 15, pp. 7036–7039, 2009.
- [104] D. Tasis, D. Kastanis, C. Galiotis, and N. Bouropoulos, “Growth of calcium phosphate mineral on carbon nanotube buckypapers,” *Physica Status Solidi B*, vol. 243, no. 13, pp. 3230–3233, 2006.
- [105] D. Pan, Y. Wang, Z. Chen, T. Yin, and W. Qin, “Fabrication and characterization of carbon nanotube-hydroxyapatite nanocomposite: application to anodic stripping voltammetric determination of cadmium,” *Electroanalysis*, vol. 21, no. 8, pp. 944–952, 2009.
- [106] S. Aryal, S. R. Bhattarai, K. C. Remant Bahadur, M. S. Khil, D. R. Lee, and H. Y. Kim, “Carbon nanotubes assisted biomimetic synthesis of hydroxyapatite from simulated body fluid,” *Materials Science and Engineering A*, vol. 426, no. 1-2, pp. 202–207, 2006.
- [107] S. Aryal, K. C. R. Bahadur, N. Dharmaraj, K.-W. Kim, and H. Y. Kim, “Synthesis and characterization of hydroxyapatite using carbon nanotubes as a nano-matrix,” *Scripta Materialia*, vol. 54, no. 2, pp. 131–135, 2006.
- [108] S. R. Bhattarai, S. Aryal, R. Bahadur et al., “Carbon nanotube-hydroxyapatite nanocomposite for DNA complexation,” *Materials Science and Engineering C*, vol. 28, no. 1, pp. 64–69, 2008.
- [109] B. Zhao, H. Hu, S. K. Mandal, and R. C. Haddon, “A bone mimic based on the self-assembly of hydroxyapatite on chemically functionalized single-walled carbon nanotubes,” *Chemistry of Materials*, vol. 17, no. 12, pp. 3235–3241, 2005.