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MDSC and TGF β Are Required for Facilitation of Tumor Growth in the Lungs of Mice Exposed to Carbon Nanotubes

Anna A. Shvedova^{1,2}, Elena R. Kisin¹, Naveena Yanamala¹, Alexey V. Tkach¹, Dmitriy W. Gutkin³, Alexander Star⁴, Galina V. Shurin³, Valerian E. Kagan^{5,6}, and Michael R. Shurin^{3,7}

Abstract

During the last decades, changes have been observed in the frequency of different histologic subtypes of lung cancer, one of the most common causes of morbidity and mortality, with a declining proportion of squamous cell carcinomas and an increasing proportion of adenocarcinomas, particularly in developed countries. This suggests the emergence of new etiologic factors and mechanisms, including those defining the lung microenvironment, promoting tumor growth. Assuming that the lung is the main portal of entry for broadly used nanomaterials and their established proinflammatory propensities, we hypothesized that nanomaterials may contribute to

changes facilitating tumor growth. Here, we report that an acute exposure to single-walled carbon nanotubes (SWCNT) induces recruitment and accumulation of lung-associated myeloid-derived suppressor cells (MDSC) and MDSC-derived production of TGF β , resulting in upregulated tumor burden in the lung. The production of TGF β by MDSC requires their interaction with both SWCNT and tumor cells. We conclude that pulmonary exposure to SWCNT favors the formation of a niche that supports ingrowth of lung carcinoma *in vivo* via activation of TGF β production by SWCNT-attracted and -presensitized MDSC. *Cancer Res*; 75(8); 1–9. ©2015 AACR.

Introduction

Currently, lung cancer is one of the most common causes of morbidity and mortality, although in 1912, it was described as "one of the rarest forms of cancer" (1). It accounts for 14% of all cancer diagnoses and up to 30% of all cancer deaths. It is the leading cause of cancer-related death in the developed world, whereby carcinoma of the lung and bronchus is the most impactful compared with the other forms of cancer (2). Etiologically, lung cancer is strongly associated with the environmental exposure, with tobacco smoking and industrial air pollution being the major risk factors. Two main types of pulmonary carcinoma related to the exposure to cigarette and industrial smoke are squamous cell carcinoma (SCC) and small-cell neuroendocrine carcinoma. These tumors usually develop from bronchial mucosa of conductive airways, where smoke particles deposit and lead to carcinogenesis. With the current efforts towards smoking cessa-

tion and a better control of industrial smoke exhausts, one would expect a decline of lung cancer prevalence. Instead, the lung cancer incidence keeps increasing (3). Moreover, although the incidence of SCC appears to have been decreased, the incidence of another type of lung cancer, adenocarcinoma, has been escalating in industrially developed countries, in contrast with still preserved prevalence of SCC in the developing countries and regions (4, 5). This tumor accounts for up to 50% of newly diagnosed lung cancer cases, and the reasons for its recently increased incidence remain poorly defined. Although the most frequently observed histologic type of lung cancer among smokers is SCC, among never smokers, adenocarcinomas are more frequent than SCC and comprise the majority of tumors (6). More than 75% of these malignancies develop from the deep portions of the lung (the acinar structures).

These epidemiologic data suggest that entirely new, possibly environmental, factors got engaged in pulmonary carcinogenesis. One of the possible candidates are nanoparticles with an estimated approximately 1,300 kinds of nanomaterials currently either in use or in testing for potential commercial applications ranging from electronic (e.g., advanced memory chips) to industrial (e.g., coatings or composites) to biomedical fields (e.g., drug delivery systems, diagnostics; ref. 7). While the risk of adverse effects of nanomaterials on the human body has still to be investigated (8), their ability to induce robust inflammatory response and fibrosis have been firmly established (9–11). The highest risk arises from occupational exposure via chronic inhalation of nanoparticles. For instance, carbon nanotubes (CNT) could be released as dust into the atmosphere during disposal or lower temperature incineration of lithium-ion secondary batteries and synthetic textiles (12). It was estimated that there could be between 20,000 and 100,000 natural and man-made

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nanoparticles per cubic centimeter in the everyday environment (13). Analysis of indoor and outdoor environmental nanoparticles revealed that their most significant fraction were carbonaceous nanoparticles, particularly CNT (14). Lung is the major entry portal and target organ for airborne CNT, which can migrate into the alveolar interstitial compartment of the lung (9, 15). In contrast to tobacco smoke particulates, CNT, due to their small size, can deposit deep in the lung and even reach the pleura (16). In spite of several enzymatic pathways for their biodegradation by inflammatory cells (17, 18), CNT are relatively biopersistent (19). Tragically, among 60,000–70,000 exposed responders during the World Trade Center (WTC) disaster, generated as a result of the combustion of fuel in the presence of carbon and metals, CNT were found in the lungs of WTC patients suffering from pulmonary diseases (20).

Recently, we have demonstrated that a single pulmonary exposure to single-walled CNT (SWCNT) accelerated growth of lung cancer in mice (21). We further uncovered that depletion of CNT-induced accumulation of myeloid-derived suppressor cells (MDSC) prevented accelerated growth of lung carcinoma. However, the key question about molecular mechanisms of this phenomenon has not been established. On the basis of bioinformatics analysis of previously obtained proteomics (22), and transcriptomics data as well as existing known factors of MDSC recruitment/function and tumor initiation/growth/progression/metastasis, we hypothesized that TGF β is the most likely candidate for: (i) CNT-induced changes in the lung, (ii) MDSC-mediated support of tumor growth, and (iii) MDSC functioning in the tumor microenvironment. Therefore, we examined the role of aberrant TGF β signaling on increased homing of MDSC and accelerated tumor progression upon SWCNT exposure. We report that CNTs upregulate TGF β production by tumor-activated MDSC and support immunosuppressive protumorigenic microenvironment in the lungs of CNT-exposed animals. Consequently, TGF β deficiency completely abrogated the CNT-induced acceleration of cancer growth in the lung. We provide evidence that CNTs are required for upregulated production of TGF β by MDSC induced by tumor cells. In turn, TGF β produced by activated MDSC was responsible for suppression of T-cell activation and proliferation. Overall, our results identify the airborne SWCNT as a potential risk factor of accelerated progression of lung carcinoma *in vivo* and uncovered immunologic mechanisms underlying this effect.

Materials and Methods

Animals

Pathogen-free C57BL/6J mice (7–8 week old) and *Tgfb1^{tm1Doe}*/J mice from Jackson Labs were individually housed and acclimated for 2 weeks. Animals were supplied with water and food *ad libitum* and housed under controlled light, temperature, and humidity conditions. All animal studies were conducted under a protocol approved by the Institutional Animal Care and Use Committee.

Preparation of SWCNT

SWCNT (CNI Inc.) were produced by the high pressure carbon monoxide (CO) disproportionation process (HiPco) technique employing CO in a continuous-flow gas phase as the carbon feedstock and Fe(CO)₅ as the iron-containing catalyst precursor, and purified by acid treatment to remove metal contaminants.

Chemical analysis trace metal (iron) in SWCNT was performed at the Chemical Exposure and Monitoring Branch (DART/NIOSH, Cincinnati, OH) using nitric acid dissolution and inductively coupled plasma-atomic emission spectrometry (ICP-AES) as described earlier (21). The mean diameter and surface area of SWCNT were 1–4 nm and 1,040 m²/g. Surface area was determined by Brunauer, Emmett and Teller (BET) analysis, and diameter and length was measured by transmission electron microscopy (TEM). The chemical cutting of SWCNT was performed as reported previously (21). TEM determined the length distribution: 228 \pm 77 nm. Atomic force microscopy and diffuse reflectance infrared Fourier Transform spectroscopy were utilized to determine structure and purity of prepared SWCNT as described (21). Stock suspensions (1 mg/mL) were prepared before each experiment in PBS and pH was adjusted to 7.0; suspensions were sonicated for 5 minutes and sterilized by autoclaving. Stock suspensions were diluted to achieve required concentrations and sonicated (three 1-minute cycles) before use.

Tumor cells, cell lines, and experimental procedures

Lewis lung carcinoma cells (LLC) and BEAS-2B cells (human bronchial epithelial cell line), were obtained from ATCC. LLC cells were maintained in RPMI1640 medium supplemented with 2 mmol/L L-glutamine, 100 U/mL penicillin, 100 μ g/mL streptomycin, 10 mmol/L HEPES, 10% heat-inactivated FBS, 0.1 mmol/L nonessential amino acids, and 1 mmol/L sodium pyruvate (Invitrogen Life Technologies, Inc). BEAS-2B cells were cultured in DMEM (5% FBS) and exposed to 0.06, 0.12, 0.24 mg/mL of SWCNT for 18 hours.

Wild-type (WT) and TGF β -deficient mice were exposed to CNT by pharyngeal aspiration (21), shown to induce alterations in the lungs similar to those caused by inhalation in special chambers (9). Briefly, after anesthesia with ketamine/xylazine (62.5 and 2.5 mg/kg s.c.), each mouse was placed on a board in a near-vertical position and a suspension of CNT (80 μ g/mouse in saline) was placed posterior in the throat to be aspirated into the lungs. Seven to 8 animals per group were utilized for the *in vivo* studies and all experiments were independently repeated at least three times. In control groups, both WT and TGF β -deficient mice were exposed to a single aspiration of PBS.

Forty-eight hours after CNT or PBS exposure, mice were inoculated with 3×10^5 LLC cells (300 μ L PBS) via the tail vein. Twenty-one days later, the animals were sacrificed and the number of visible pulmonary metastases was determined using a dissection microscope. Lungs were weighted, and right lobes were fixed in 10% formaldehyde for histopathology evaluation of hematoxylin and eosin (H&E)-stained specimens (21).

Evaluation of MDSC

For pulmonary MDSC isolation and analysis (48 hours after CNT exposure), mouse lungs were dispersed using 2% collagenase A and 0.75% DNase I (Roche Diagnostics GmbH) in RPMI1640 medium supplemented with 10% FBS at 20°C for 1 hour. Spleens were harvested, grounded, and filtered through a 70 μ m cell strainer. Red blood cells were lysed with lysing buffer (155 mmol/L NH₄Cl in 10 mmol/L Tris-HCl buffer pH 7.5, 25°C) for 3 minutes. After RBC lysis, cells were washed, labeled with anti-CD11b, anti-Ly6G, anti-Ly6C, anti-Gr-1, and anti-CD45 antibodies (Biolegend Inc.) directly conjugated to FITC, PE, PE/Cy7, APC/Cy7, or Alexa700, and analyzed by flow cytometry (BD LSR II instrument, BD Biosciences). Data on MDSC counts in the lung

and spleen are presented as the percentage of total cells and CD45⁺ cells in the tested tissue.

CD11b⁺ Gr-1⁺ MDSC were isolated from the lungs of WT and TGF β -deficient mice exposed to SWCNT or saline by magnetic cell sorting using a mouse MDSC Isolation Kit (MACS, Miltenyi Biotec) according to the manufacturer's instructions. Syngeneic T cells were isolated from the spleens of WT mice using T-cell enrichment columns and activated with ConA (5 hours, 2.5 μ g/mL, Sigma) for 24 hours. For functional studies, isolated MDSC were cocultured with preactivated syngeneic splenic T cells (1:5 ratio) for 48 hours and the levels of IL2 production by T cells were assessed by ELISA (R&D Systems Inc.). T-cell proliferation was measured by uptake of ³H-thymidine (1 μ Ci/well, 5 Ci/mmol; DuPont-NEN) pulsed for 16–18 hours after 2 days in culture. Cells were harvested on GF/C glass fiber filters (Whatman Intl. Ltd) using MACH III Microwell Harvester (Tomtec). ³H-thymidine incorporation was determined on MicroBeta TRILUX liquid scintillation counter (WALLAC) and expressed as count per minute (cpm). Alterations of T-cell proliferation by MDSC are shown as Index of Stimulation (IS) calculated as a ratio of treated to nontreated (control) T cells.

Production of TGF β by MDSC was determined by assessing the levels of TGF β 1 in cell-free supernatants by ELISA (R&D Systems).

Bioinformatics-based identification of CNT-induced and MDSC-mediated factors facilitating accelerated growth of lung cancer

The list of mediators that play a key role in MDSC recruitment/function was created on the basis of the published data (23, 24). The list of genes encoding cytokines, chemokines, and growth factors associated with tumor initiation/progression/growth/metastasis in lung cancer was generated through the use of IPA software tool (Ingenuity Systems, www.ingenuity.com). Finally, the list of inflammatory mediators differentially upregulated (>1.5-fold in at least two different concentrations) upon SWCNT exposure was composed on the basis of the data obtained from microarray analysis studies of BEAS-2B cells.

High-density oligonucleotide array expression analysis

Total RNA from BEAS-2B cells cultured with medium or SWCNT were isolated using RNeasy (Qiagen). Further sample preparation for microarray analysis was carried out as described by the manufacturer (Affymetrix). Briefly, total RNA (12 μ g) was used for the preparation of double stranded cDNA using an oligonucleotide (dT)24 primer with a T7 RNA polymerase promoter sequence at its 5' end. After second strand synthesis, a labeled cRNA transcript was generated from the cDNA in an *in vitro* transcription reaction using Enzo BioArray high yield RNA transcript labeling (Enzo Diagnostics Inc.). The labeled antisense cRNA was purified using RNeasy (Qiagen) and each cRNA sample was fragmented (94°C for 35 minutes) in the presence of Tris-acetate (40 mmol/L, pH 8.1), potassium acetate (100 mmol/L), and magnesium acetate (30 mmol/L).

The fragmented cRNA was mixed with eukaryotic hybridization control oligonucleotides (20 \times ; BioB, BioC, BioD, cre at 1.5, 5, 25, and 100 pmol/L, respectively), control oligonucleotide B2, herring sperm DNA (10 mg/mL), acetylated BSA (50 mg/mL), and hybridization buffer (2 \times) to form the hybridization cocktail. This cocktail, was heated (99°C for 5 minutes; and 45°C for 5 minutes) before introduction to microarray cartridge (U133A). Hybridiza-

tion was allowed to proceed (45°C in rotisserie oven set at 60 rpm) for 16 hours. Following hybridization, the arrays were washed and stained using the GeneChip fluidics station protocol EukGE-WS2. After washing and staining, probe arrays were scanned using Gene Array 2500 scanner (Affymetrix). ImageGene 3.0 software (BioDiscovery Inc.) was used to quantify, correct for background noise, and normalize signals from hybridization chip. Thus, obtained data were filtered on the basis of signal intensity and detection calls. To identify genes differentially expressed between control and SWCNT exposed groups, we used univariate F-test (after log2 conversion of the mRNA expression abundance, FPKM) between control and exposed groups with a *P* value cut-off of 0.05 and false discovery rate below 0.05 using statistical package R.

Statistical analysis

Results were analyzed using one-way ANOVA and Student unpaired *t* test with Welch correction for unequal variances. All experiments were repeated at least twice and the results are presented as the means \pm SEM. *P* values of <0.05 were considered to be statistically significant.

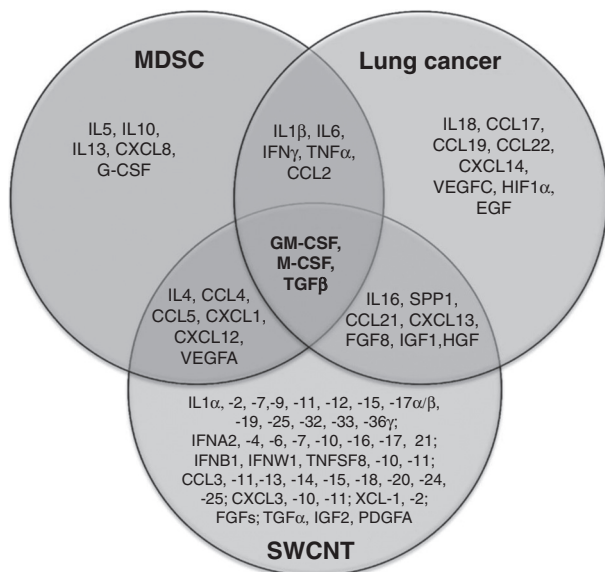
Results

Bioinformatics analysis of inflammatory mediators common to CNT exposure and MDSC-driven immunosuppression in lung cancer

Multifactorial processes of tumor progression and metastasis are strongly associated with chronic inflammation whereby several cytokines, chemokines, and growth factors produced by cancer cells as well as modified immune cells, including MDSC, play essential roles. On the basis of the available literature, we used bioinformatics to generate lists of key cytokines, chemokines, and growth factors associated with (i) MDSC recruitment and function, (ii) initiation, progression, metastasis, and growth of lung tumors, and (iii) SWCNT exposures as summarized in Fig. 1. A total of three factors, macrophage colony-stimulating factor (M-CSF), granulocyte/macrophage colony-stimulating factor (GM-CSF), and TGF β , were common to all three selected categories. This analysis suggests that the upregulation of GM-CSF, M-CSF, and TGF β upon SWCNT exposure may lead to increased accumulation of MDSC in the lung and accelerated growth of lung cancer. To explore mechanisms of CNT in pulmonary metastatic tumor growth, we chose to experimentally assess the effects of TGF β .

Accelerated tumor growth induced by SWCNT is blocked in TGF β -deficient mice

Injection of LLC cells to control WT mice caused multiple bilateral pulmonary tumor nodules by day 21. Histologically, these tumors showed characteristic features of poorly differentiated non-small cell carcinoma. Exposure of WT mice to SWCNT before tumor cell injection resulted in significant acceleration of tumor growth revealed by up to 5-fold increase in the weight of the lungs (the overall tumor burden), up to 2.5-fold elevation of the number of visible pulmonary macrometastasis, and up to 3-fold increase in the total area of tumor nodules upon histopathologic evaluation of the lung tissues (Fig. 2, *P* < 0.05). SWCNT did not change the typical morphologic features of tumor, but accelerated tumor growth and the appearance of intratumoral necrosis zones, associated with rapid tumor growth.

**Figure 1.**

Venn diagram of cytokines, chemokines, and growth factors that (i) affect MDSC generation, recruitment, expansion, and function; (ii) facilitate lung cancer growth, progression, and metastasis; (iii) are upregulated (>1.5-fold) upon SWCNT exposure. The list of mediators that play a key role in MDSC recruitment/function was created on the basis of the published data (23, 24). The list of genes encoding cytokines, chemokines, and growth factors associated with tumor initiation/progression/growth/ metastasis in lung cancer was generated through the use of IPA software tool (Ingenuity Systems, www.ingenuity.com). Finally, the list of inflammatory mediators differentially upregulated (>1.5-fold in at least two different concentrations) upon SWCNT exposure was composed on the basis of the data obtained from microarray analysis studies of BEAS-2B cells.

In control TGFβ-deficient mice, injection of LLC cells led to the appearance of pulmonary metastases, similar in size and morphology to those in WT mice (Fig. 2A–C). However, the effect of CNT on tumor growth was completely abrogated in TGFβ-deficient animals: neither the average lung weight (Fig. 2A), nor the numbers of detectable tumor nodules (Fig. 2B) were altered in TGFβ-deficient mice after exposure to CNT. Histopathologic examination of H&E-stained tissue specimens confirmed the absence of difference in the total area of tumor nodules between CNT-exposed and saline-exposed TGFβ-deficient mice receiving tumor cells after exposure (Fig. 2C). These data indicate that exposure of SWCNT promoted establishment and growth of lung carcinoma in mice *in vivo* in a TGFβ-dependent manner.

TGFβ deficiency does not abrogate acute accumulation of MDSC in the lung after a single pulmonary exposure to SWCNT

Because depletion of MDSC induced by CNT exposure before administration of tumor cells completely abrogated increase in lung cancer growth (21), it is likely that MDSC may form the premalignant niches supporting initial survival and growth of tumor cells in the lungs. Assuming that MDSC contribute to TGFβ-mediated metastasis (25), it is possible that CNT may induce early MDSC accumulation in TGFβ-deficient mice. To test this, we determined the accumulation of MDSC in the lungs 48 hours after SWCNT aspiration because the elimination of this acute MDSC response in TGFβ-deficient animals might explain the abrogation of the tumor-promoting activity of CNT in *Tgfb1^{tm1Doe}*

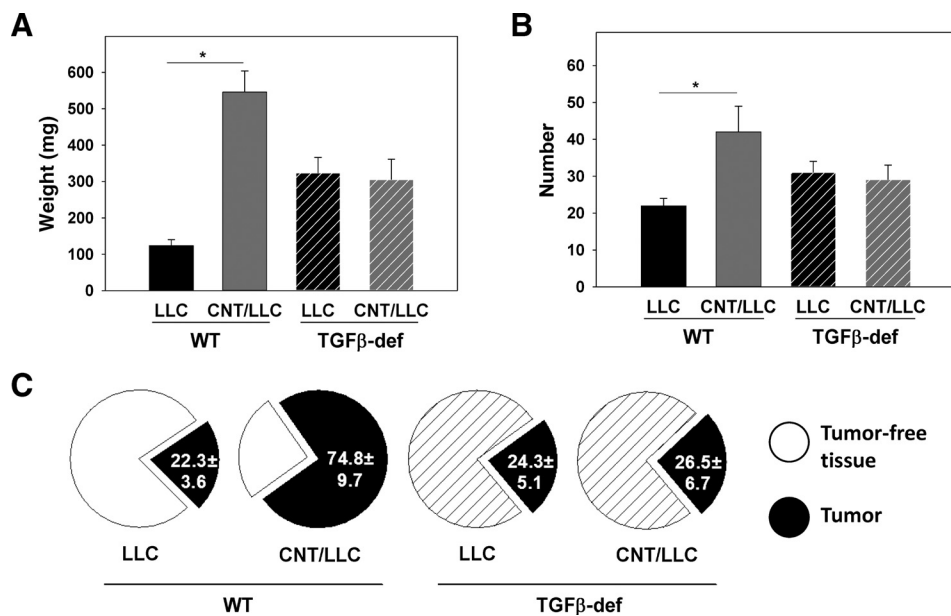
mice shown in Fig. 2. However, the results showed that TGFβ is not involved in the initial recruitment of MDSC in the lungs and lymphoid tissues by acute SWCNT exposure (Fig. 3). In fact, similar to WT mice (21), SWCNT significantly ($P < 0.05$) upregulated homing of granulocytic MDSC in lymphoid and non-lymphoid tissues in TGFβ-deficient animals: elevated up to 3-fold numbers of CD11b⁺Ly6G⁺Ly6C^{low} MDSC were detected in the lungs and spleens of SWCNT-treated tumor-free animals 48 hours after CNT administration (Fig. 3A and B). These data indicate that TGFβ was not involved in SWCNT-induced recruitment of MDSC to the lungs to form the premalignant niches. Thus, TGFβ plays a different role, possibly participating in MDSC functions facilitating CNT-induced enhanced growth of lung carcinoma.

SWCNT presensitize MDSC to tumor-induced activation of the TGFβ-mediated immunosuppressive activity

One of the potential, although not fully characterized, immunosuppressive mechanisms of MDSC is the production of TGFβ (26, 27). To assess the role of MDSC-derived TGFβ in CNT-induced MDSC-mediated immunosuppressive premalignant niche in the lung, pulmonary MDSC were isolated from control and SWCNT-exposed WT and *Tgfb1^{tm1Doe}* mice, treated with control and LLC-conditioned media, cocultured with preactivated syngeneic T cells, and then T-cell activity was assessed by IL2 production (Fig. 4A). Analysis of MDSC-mediated inhibition of T-cell activation (Fig. 4B) revealed that only MDSC harvested from WT SWCNT-exposed mice, but not from saline-exposed mice, and preincubated with tumor-conditioned medium were able to suppress T cells *ex vivo* up to 2-fold ($P < 0.05$). Importantly, the immunosuppressive effect of MDSC was abrogated if they were isolated from TGFβ-deficient mice. These results suggest that MDSC exposed to the SWCNT-modified lung microenvironment for even less than 48 hours *in vivo* are sensitive to lung carcinoma-induced emergence of the immunosuppressive potential mediated by TGFβ.

Although these results provide strong evidence that tumor-derived factors play a key role in activating the immunosuppressive phenotype of CNT presensitized MDSC, they were based on the *in vitro* treatment of MDSC with the LLC-conditioned medium. To explore the *in vivo* role of tumor cells in activating pulmonary MDSC, we further isolated MDSC from saline- and SWCNT-exposed mice bearing lung cancer. Tumor-free mice served as a control. The design and results of these studies are shown in Fig. 5 and demonstrate that *in vivo* generated lung MDSC required *in vivo* interaction with tumor cells to acquire an immunosuppressive phenotype assessed by their ability to suppress proliferation of syngeneic T cells. Furthermore, the ability of MDSC to inhibit T cells was aborted if pulmonary MDSC were harvested from TGFβ-deficient animals (Fig. 5, $P < 0.05$). Together, the *in vitro* and *in vivo* data suggest that MDSC attracted to the lungs by SWCNT exposure are more sensitive to the activation in the lung cancer microenvironment than control pulmonary MDSC, and that the ability of lung MDSC to inhibit T cells is mediated by TGFβ.

This encouraged us to further examine direct effects of CNT on MDSC and TGFβ production by MDSC. To this end, MDSC were directly treated with SWCNT *in vitro* and TGFβ1 expression was evaluated. We found that, although CNT and LLC did not markedly increased TGFβ levels in MDSC cultures (189.2 ± 19.6 ng/mL vs. 201.1 ± 18.2 ng/mL and 229.4 ± 24.4 ng/mL in

**Figure 2.**

TGF β deficiency aborts SWCNT-induced accelerated growth of lung carcinoma. Wild type (WT) and TGF β -deficient (TGF β def) mice received SWCNT by pharyngeal aspiration 48 hours before intravenous tumor cell injection and were sacrificed 3 weeks later. The lungs were collected for determining the weight (A), visualization of macroscopic tumor nodules (B), and histochemical analysis of micrometastases after H&E staining (C). The average weight of the lungs, the number of tumor nodules, and the average collective areas of lung carcinoma on tissue slides were calculated from three independent experiments (5–6 mice/group in each) and are shown for LLC and CNT/LLC groups in both WT and TGF β -deficient mice. LLC, mice received a single aspiration of PBS and 48 hours later were injected intravenously with LLC tumor cells; CNT/LLC, mice were pretreated with SWCNT 48 hours before administration of LLC cells. *, $P < 0.05$ (Student t test, $N = 3$).

control, CNT-treated and LLC-treated cells, respectively), concomitant treatment of MDSC with SWCNT and LLC-conditioned medium significantly increased TGF β in MDSC cultures (313.7 ± 21.2 ng/mL, $P < 0.05$; Fig. 6). Thus, SWCNT augment TGF β expression by MDSC induced by lung cancer cells.

Overall, we established a potential mechanism of CNT-induced enhanced growth of lung carcinoma, which is mediated by an immediate recruitment and accumulation of MDSC in the lungs and formation of specific microenvironmental niches that support tumor cell growth. Although TGF β was not involved in the initial recruitment of MDSC to the lung by SWCNT, its deficiency completely blocked accelerated tumor progression in the lungs after SWCNT exposure. CNT-triggered changes in the lung microenvironment encouraged accumulation of MDSC that were sensitive to tumor-induced activation, leading to TGF β -dependent suppression of T cells.

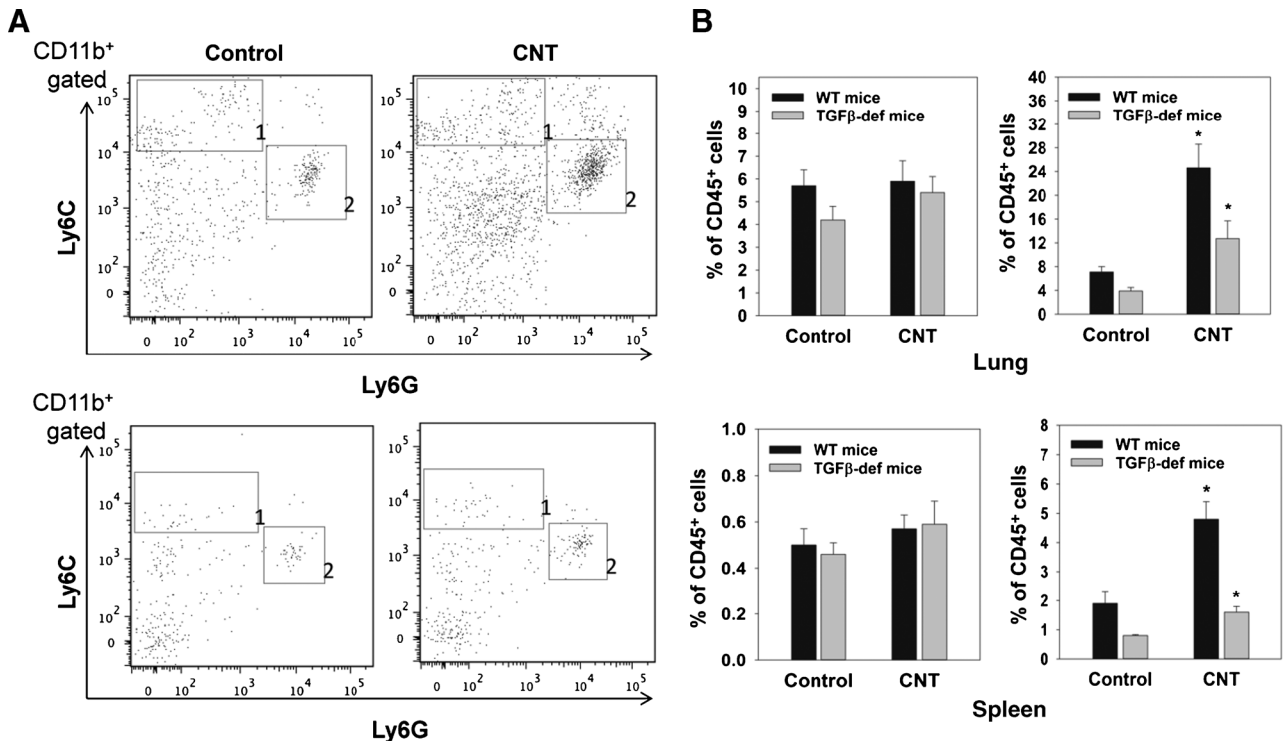
Discussion

A huge diversity of carbonaceous nanomaterials is on the way to multiple industrial and biomedical applications; therefore, understanding their toxicity is critical for their commercialization (28). Among those, CNT have been reported to have several adverse effects on cellular and organismal levels, which may be predictive of detrimental human health effects upon exposures (29–31). For instance, *in vitro* studies indicate that single- and multi-walled CNT may be genotoxic, demonstrating a carcinogenic potential. Chronic exposure to CNT was shown to induce DNA damage and increase mutation frequency in mouse embryonic cells and human epithelial cells (32, 33). CNT induce mitotic abnormality with one rather than two mitotic spindle poles, a

potential mechanism for the impaired cell division (34). Many studies have reported that CNT can induce apoptosis, DNA damage, and activation of major regulatory pathways, MAPKs, AP-1, NF- κ B, and Akt, all of which recapitulate key molecular events involved in asbestos-induced lung cancer (31, 35). Moreover, Pacurari and colleagues reported that MWCNT exposure affects a subset of lung cancer prognostic biomarkers in mouse lungs (36) and Wang and colleagues showed that chronic exposure to SWCNT *in vitro* caused malignant transformation of human lung epithelial cells (37).

In the context of tumorigenesis and tumor/host relationships, important are the effects of CNT on pulmonary microenvironment. Several animal studies demonstrated that exposure to CNT induced acute and chronic inflammatory response, chronic granulomatous reaction, and substantial interstitial fibrosis in the lungs (9, 11, 16, 29, 30). Fibrosis may be viewed as a precursor to lung cancer. In fact, pulmonary scarring and lung cancer were found to occur in the same lung regions and extend over time, indicating that lung cancer could originate from lung scarring (38). Overall, there are two potential protumorigenic mechanisms associated with CNT exposure: (i) direct carcinogenic effects on pulmonary cells and (ii) alteration of inflammatory pulmonary milieu making it conducive to cancer development. Surprisingly, the second mechanism, acute CNT effects on host–tumor interactions and growth of tumors has not been yet considered.

Previously, we have reported that CNT promote tumor establishment and lung tumor growth by altering the tissue microenvironment, specifically by facilitating early MDSC accumulation in the lungs, as depletion of MDSC abrogated protumorigenic effect of acute exposure to CNT (21). It is likely that inflammatory MDSC induced by CNT support the initial tumor cell homing in the lungs

**Figure 3.**

TGFβ deficiency does not abrogate acute accumulation of MDSC in the lung and spleen after a single pulmonary exposure to SWCNT. Wild-type (WT) and *Tgfb1^{tm1Doe}* mice received SWCNT by pharyngeal aspiration and the levels of monocytic CD11b⁺Ly6G^{neg}Ly6C^{high} (area 1) and granulocytic CD11b⁺Ly6G⁺Ly6C^{low/neg} (area 2) MDSC were assessed by flow cytometry in the lymphoid tissues and lungs. The results of flow cytometry analysis of MDSC accumulation in tumor-free *Tgfb1^{tm1Doe}* mice 48 hours after SWCNT aspiration are shown from a representative experiment (A; CD11b⁺ gated cells are shown). Statistical analysis of data from three independent experiments (5–6 mice/group in each) is shown as the mean ± SEM and demonstrates accumulation of polymorphonuclear MDSC in different tissues in tumor-free mice 48 hours after SWCNT aspiration. *, $P < 0.05$ (Student *t* test, $N = 3$; B). Control, mice received a single aspiration of PBS. CNT, mice received SWCNT once by pharyngeal aspiration.

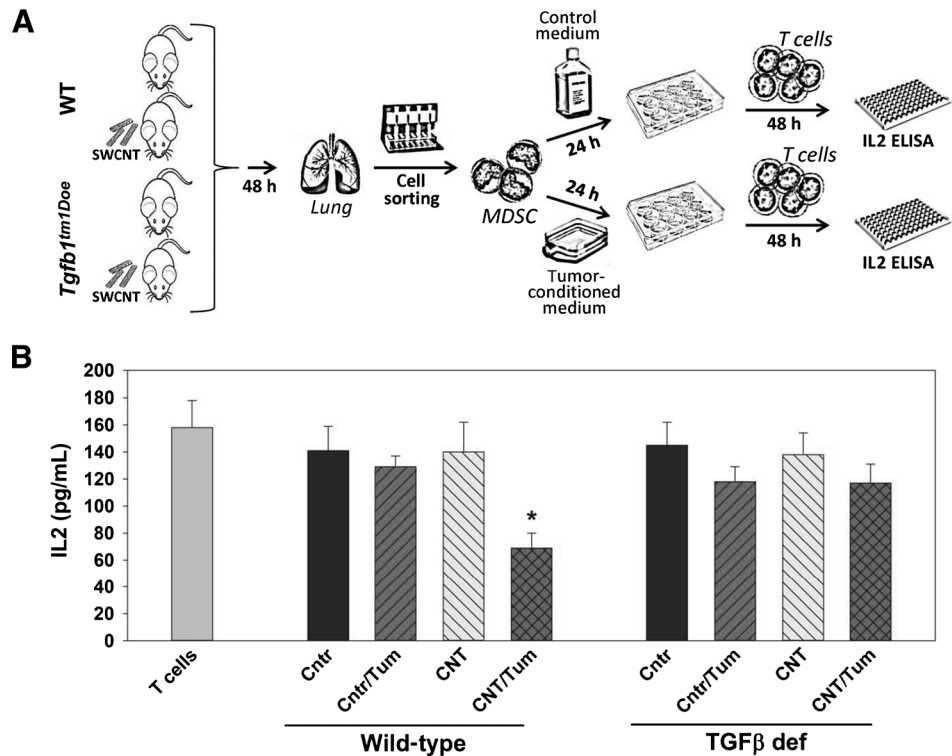
and then become polarized into tumor-associated MDSC. The latter are known to block the development of antitumor immunity hence facilitate tumor growth by producing specific growth factors and cytokines that also stimulate intratumoral neoangiogenesis (39). However, the specific mechanisms through which SWCNT affect MDSC–tumor cell interactions and induce immunosuppressive activity have not been deciphered. Bioinformatics analysis of previously published data revealed that 3 growth factors, GM-CSF, G-CSF, and TGFβ are common to CNT, formation, progression of lung cancer, and accumulation and immunosuppressive function of MDSC (Fig. 1). These growth factors have been shown to be expressed in tumor lesions (40). While M-CSF stimulates the differentiation of granulocytes or macrophages (41), GM-CSF and TGFβ have been reported to have a strong impact on MDSC expansion (40, 42, 43). Thus, it is possible that all three of the factors, GM-CSF, M-CSF and TGFβ, are involved in the accelerated tumor growth after SWCNT exposure. Notably, TGFβ has been identified as a metastasis promoter (44). Given a recently reported upregulation of TGFβ in the lungs of mice after chronic inhalation of multiwalled CNT (45), we speculated that TGFβ could be responsible for the increased homing of MDSC and accelerated tumor progression responses upon SWCNT exposure.

Here, we uncovered the key function of TGFβ in SWCNT-induced and MDSC-mediated formation of premalignant niches

and acceleration of lung carcinoma establishment *in vivo* (Fig. 2). TGFβ is involved in many biologic processes, including cell proliferation, differentiation, apoptosis, embryogenesis, as well as cancer (46, 47). Alterations in TGFβ signaling have significant effects on tumor initiation and progression (46) and the lack of TGFβ signaling may promote collective cancer cell invasion and tumor progression (48). One of the identified mechanisms of TGFβ-dependent tumor promotion is the recruitment of MDSC to the tumor microenvironment (25). TGFβ is also an important suppressive cytokine produced by MDSC for inhibiting the anti-tumor immunity (26). TGFβ may also suppress VEGF-mediated angiogenesis in cancer metastasis (49). Several reports showed that blocking of TGFβ by an antibody or soluble receptor inhibited tumor growth (50–52). Moreover, TGFβ can suppress anti-tumor immune responses and create a local environment of immune tolerance (46). Elevated levels of serum TGFβ1 and its association with metastases were independently detected in patients with different types of cancer (53). Furthermore, in lung cancer, increased expression of TGFβ was correlated with advanced stages of disease malignancy, metastases, and with decreased survival rates (54). There are several mechanisms through which TGFβ can accelerate growth of lung carcinoma. Upregulated levels of TGFβ upon SWCNT exposure could (i) participate directly in recruiting/expanding MDSC, (ii) contribute to the suppression of T-cell responses by activating/differentiating

Figure 4.

TGF β mediates inhibition of T cells by lung MDSC isolated from SWCNT-exposed mice and treated with lung cancer-derived factors *in vitro*. A, experimental protocol. WT and *Tgfb1^{tm1Doe}* mice received SWCNT or saline by pharyngeal aspiration and 48 hours later MDSC were isolated from the lungs as described in Materials and Methods. MDSC were then treated with LLC-conditioned medium and control medium for 24 hours, washed, and cocultured with ConA preactivated syngeneic T cells. Inhibition of T-cell activation was determined in 48 hours by assessing the levels of IL2 in cell-free supernatants by ELISA (B). The results are shown as the mean \pm SEM (triplicate measurements for each mouse, 5–6 mouse/group, two independent experiments). *, $P < 0.05$, versus all other groups (one-way ANOVA). Control (cntr), MDSC from saline-treated mice; CNT, MDSC from SWCNT exposed mice; Tum, MDSC treated with LLC-conditioned medium; T cells, control T cells cultured without MDSC.

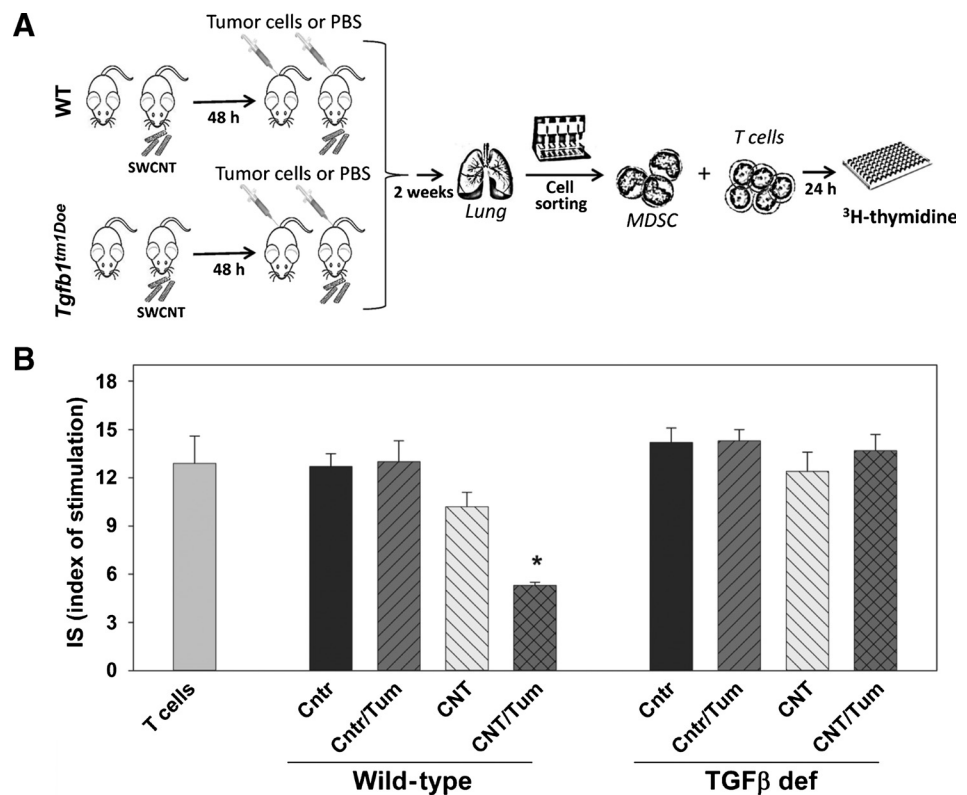


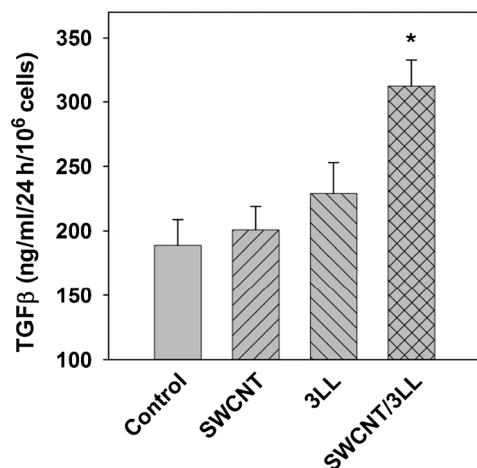
MDSC to secrete IL10 and TGF β , and (iii) contribute to indirect suppression by inducing Tregs through membrane binding on MDSC (39, 55). However, the mechanisms of induction of TGF β

expression and the source of this cytokine in tumor models have not been understood, except for the fact that tumor cells are known to produce this cytokine.

Figure 5.

SWCNT predispose pulmonary tumor-associated MDSC to inhibit T-cell proliferation via TGF β 1 pathways *in vivo*. A, experimental protocol. WT and *Tgfb1^{tm1Doe}* mice received SWCNT or saline by pharyngeal aspiration and LLC cells intravenously 48 hours later. MDSC were isolated from the lungs 2 weeks later and cocultured with ConA preactivated syngeneic T cells. Inhibition of T-cell proliferation was determined in 48 hours by 3 H-thymidine incorporation and expressed as index of stimulation (IS;B). The results are shown as the mean \pm SEM (triplicate measurements for each mouse, 5 mouse/group, $N = 2$). *, $P < 0.05$, versus all other groups (one-way ANOVA). Control (cntr), saline aspiration; CNT, SWCNT aspiration; Tum, injection of LLC; T cells, control T cells cultured without MDSC.



**Figure 6.**

Exposure of MDSC to SWCNT and tumor-derived factors upregulates TGFβ expression. MDSC were isolated from the bone marrow and cultured with saline (cntr), SWCNT (6.25 μg/mL), LLC conditioned medium (25% v/v) overnight. MDSC were then collected, washed, and cultured for 24 hours. The levels of TGFβ1 in cell-free medium were assessed by ELISA.

*, $P < 0.05$ vs. control (ANOVA, triplicate wells, $N = 3$).

Here, we show that TGFβ is not involved in the initial recruitment and accumulation of MDSC to the lungs induced by SWCNT (Fig. 3), although TGFβ deficiency abrogates the protumor effect of CNT mediated by MDSC. This suggests that TGFβ released by MDSC in the lung may be involved in CNT-induced upregulation of tumor growth. Experimentally, this has been examined using the *ex vivo* model systems where MDSC isolated from control and CNT-exposed mice were treated with LLC-conditioned medium and then tested for their ability to suppress proliferation of T lymphocytes. We demonstrated that the *in vivo* exposure to SWCNT rendered lung MDSC sensitive to tumor-induced expression of TGFβ, which was responsible for the inhibition of T-cell activity by MDSC. This was further supported by the results obtained in another *ex vivo* model where MDSC were harvested from tumor-bearing CNT-exposed mice and were shown to inhibit T-cell proliferation in TGFβ-dependent manner. In our tumor model, although LLC cells can produce TGFβ, this source of the cytokine cannot play a critical role in the negative regulation of tumor immunosurveillance because LLC-bearing TGFβ-deficient

mice were resistant to SWCNT-induced acceleration of tumor establishment. Considering that TGFβ produced by CD11b⁺ Gr-1⁺ cells is necessary for downregulation of cytotoxic T-cell-mediated tumor immunosurveillance (27) and our data demonstrating direct effect of CNT on tumor-induced TGFβ production by MDSC, our combined findings uncovered a new pathway through which acute pulmonary exposure to CNT changes the interaction between myeloid regulatory cells and malignant cells to benefit tumor growth and metastasis *in vivo*.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Disclaimer

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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MDSC and TGF β Are Required for Facilitation of Tumor Growth in the Lungs of Mice Exposed to Carbon Nanotubes

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