High-Resolution Mapping of Tumor Redox Status by Magnetic Resonance Imaging Using Nitroxides as Redox-Sensitive Contrast Agents

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Abstract
Purpose: There is considerable research directed toward the identification and development of functional contrast agents for medical imaging that superimpose tissue biochemical/molecular information with anatomical structures. Nitroxide radicals were identified as in vivo radioprotectors. Being paramagnetic, they can provide image contrast in magnetic resonance imaging (MRI) and electron paramagnetic resonance imaging (EPRI). The present study sought to determine the efficacy of nitroxide radioprotectors as functional image contrast agents.

Experimental Design: Nitroxide radioprotectors, which act as contrast agents, were tested by EPRI and MRI to provide tissue redox status information noninvasively.

Results: Phantom studies showed that the nitroxide, 3-carbamoyl-PROXYL (3CP), undergoes time-dependent reduction to the corresponding diamagnetic hydroxylamine only in the presence of reducing agents. The reduction rates of 3CP obtained by EPRI and MRI were in agreement suggesting the feasibility of using MRI to monitor nitroxide levels in tissues. The levels of 3CP were examined by EPRI and MRI for differences in reduction between muscle and tumor (squamous cell carcinoma) implanted in the hind leg of C3H mice simultaneously. In vivo experiments showed a T1-dependent image intensity enhancement afforded by 3CP which decreased in a time-dependent manner. Reduction of 3CP was found to be the dominant mechanism of contrast loss. The tumor regions exhibited a faster decay rate of the nitroxide compared to muscle (0.097 min⁻¹ versus 0.067 min⁻¹, respectively).

Conclusions: This study shows that MRI can be successfully used to co-register tissue redox status along with anatomic images, thus providing potentially valuable biochemical information from the region of interest.

Magnetic resonance imaging (MRI) provides images with useful spatial and temporal resolutions and aids in the diagnosis of pathologic conditions in soft tissue. In addition to detailed anatomic information from such scans, suitable contrast agents provide important functional information pertaining to blood flow, perfusion, etc. (1). Most contrast agents used for T1-contrast enhancement contain paramagnetic entities such as the Gd³⁺ complexes and Mn²⁺ complexes. More recently, superparamagnetic iron oxide particles are being used as T2* contrast agents in MRI especially in cell tracking (2). Nitroxide radicals are organic molecules that have a single unpaired electron and therefore have the potential to provide T1 contrast similar to gadolinium complexes. Feasibility of nitroxide radicals as T1 contrast agents in MRI has been examined (3–5) before their use for in vivo EPR imaging as probes (6). However, nitroxide spin probes were reported to be not optimal as MRI contrast agents due to their rapid in vivo reduction to the diamagnetic hydroxylamine (8–11). In addition to their biological instability, the relaxivity is lower compared with Gd³⁺-based contrast agents due to the fact that nitroxide probes have only one unpaired electron, as against seven for Gd³⁺. Because of these two characteristics, nitroxide radicals were considered not advantageous as contrast agents for MRI as it was making its entry into diagnostic radiology in the 1980s.

Nitroxide radicals are redox-active species which participate in cellular redox reactions by being oxidized or reduced by cellular redox species. Nitroxides were shown to undergo oxidation to the corresponding oxoammonium cation by superoxide (12, 13) and hypervalent heme species (14). By participating in such redox reactions, they mimic enzymatic actions of superoxide dismutase and catalase. Nitroxides can also be reduced to the corresponding hydroxylamines by...
reductants such as ascorbate, semiquinone radicals, and also by intercepting reducing equivalents from the mitochondrial electron transport chain (10). These features confer to them antioxidant/protective capabilities which may underlie the observed beneficial effects in several pathologic conditions where free radicals are implicated (15). Thus, nitroxides can undergo one-electron oxidation or reduction in the presence of appropriate reactants.

Hypoxic conditions in the tumor microenvironment (16, 17), tissue redox status (18, 19), and oxidative stress accompanying generation of hydroxyl radical (20, 21) and/or superoxide (13, 22) will enhance the conversion of the paramagnetic nitroxide radicals to the corresponding diamagnetic products. In contrast, oxidizing conditions, such as exposure to hydrogen peroxide, could inhibit in vivo reduction of nitroxide radical as well as reoxidize hydroxylamine to the original nitroxide radicals (23). Nitroxide radicals, because of their ability to participate in cellular redox reactions, have been used as spin probes in electron paramagnetic resonance (EPR) imaging to monitor in vivo redox status (6, 17, 24, 25). Therefore, monitoring the rate of transformation of nitroxides to the corresponding diamagnetic species by EPR imaging can provide in vivo assessment of redox status in experimental animals. Such redox mapping based on redox-sensitive paramagnetic spin probes has been carried out by EPR imaging. Although useful information pertaining to cellular redox status was obtained from such studies, often this information could not be associated with specific anatomic regions especially in the heterogeneous environments typical in tumors. In addition, the spatial and temporal resolutions in EPR images are significantly poorer than MRI modalities.

Although nitroxides compare unfavorably to conventional \( T_1 \) contrast agents such as \( \text{Gd}^{3+} \) complexes in terms of relaxivity, being cell permeable, their volume distribution is significantly greater. This can partially compensate for their lower relaxivity compared with the cell-impermeable gadolinium complexes and provide useful \( T_1 \) contrast enhancement per unit volume similar to unchelated \( \text{Mn}^{2+} \) (2). In addition, whereas they were initially evaluated and found suboptimal in the 1980s (3–5), current MRI scanners operating at field strengths >1 T with better signal/noise ratio and efficient pulse sequences once again make it worthwhile reconsidering nitroxides as potential \( T_1 \) contrast agents, keeping in mind the recent studies showing their therapeutic capabilities (15, 26). In this study, the five-membered nitroxide 3CP was evaluated by both EPR imaging and \( T_1 \)-weighted MRI in phantom objects and in vivo to determine whether MRI could measure redox transformations of nitroxides and thus provide a high-resolution assessment of tissue redox status.

Materials and Methods

Chemicals. Carbamoyl-PROXYL [3-carbamoyl-2,2,5,5-tetramethylpyrrolidine-N-oxyl (3CP)] was purchased from Sigma-Aldrich Chem. Co. (St. Louis, MO). Solutions of 4 mmol/L 3CP and 10 mmol/L ascorbic acid were prepared in 50 mmol/L phosphate buffer (pH 7.4) for phantom experiments. For in vivo experiments, 3CP was dissolved in deionized water to obtain a 300 mmol/L (isotonic) solution for i.v. injection to mice.

Animals. Female C3H mice were supplied by the Frederick Cancer Research Center, Animal Production (Frederick, MD). Animals, received at 6 weeks of age, were housed five per cage in climate-controlled, circadian rhythm–adjusted rooms and were allowed food and water ad libitum. Experiments were carried out in compliance with the Guide for the Care and Use of Laboratory Animal Resources (1996). National Research Council, and approved by the National Cancer Institute Animal Care and Use Committee. Experiments were done within 4 weeks of their arrival at the facility. Their measured body weight before the experiments was in the range of 22 to 27 g. A squamous cell carcinoma (SCCVII) tumor was implanted and grown on the right hind leg for a week.

Phantom experiments. A cylindrical phantom (internal diameter, 1.27 cm) was set in the center of a Litz coil resonator (30-mm diameter and 50-mm length) in a 300-MHz EPR or a birdcage-type MRI coil. The cylinder and the connected lines were filled with 50 mmol/L phosphate buffer (pH 7.4). The same volume of 4 mmol/L...
3CP solution and 10 mmol/L ascorbic acid solutions was simultaneously delivered into the cylinder with the same flow rate using a stopped-flow mimicking system, and the flow was stopped after the internal volume of the cylinder was completely replaced by the reaction mixture. Scans were started 5 minutes before starting the reaction and repeated at 2.3-minute intervals for EPR imaging and at 30-second intervals for MRI.

**Total nitroxide volume in tissues.** A 300 mmol/L 3CP solution (isotonic) was injected at a dose of 1.5 μmol/g b.w. in the tail vein of squamous cell carcinoma tumor–bearing mice under isoflurane (1.5%) anesthesia. The normal femoral muscle and tumor tissues were collected as a function of time (5, 7.5, 10, 15, and 20 minutes). Then, these samples were diluted in 4-fold volume of PBS, homogenized, and mixed with ferricyanide solution (2 mmol/L in final), which quantitatively converts the hydroxylamine produced as a result of in vivo reduction back to the nitroxide radical form. The sample (100 μL) was measured by X-band EPR and the concentration of nitroxyl contrast agent was determined from standard curve of nitroxyl contrast agent dissolved in PBS, which included ferricyanide (2 mmol/L). The operating conditions of X-band EPR spectrometer were as follows: microwave frequency, 9.4 GHz; microwave power, 1 mW; modulation frequency, 100 kHz; modulation width, 1 Gauss; sweep rate, 25 Gauss/ min; and time constant, 0.064 s.

**In vivo two-dimensional EPR imaging experiments.** Mice were anesthetized by isoflurane (1.5%) in medical air (700 mL/min). The mouse was placed in a special lucite mouse holder with adhesive tape and put in the Litz coil resonator (30-mm diameter and 50-mm length; ref. 27). The tail vein was cannulated for the injection of 3CP. The core temperature of the mouse was maintained at −37°C using an air heater. Data acquisition was started immediately after injecting 3CP solution.
(1.5 μmol/g b.w.). EPR imaging data acquisition was carried out using a home-built 300 MHz CW EPR imager (28). A set of 12 projections were obtained every 1.9 minutes. Other EPR conditions were as follows: microwave frequency, 300 MHz; magnetic field strength, 10 mT; microwave power, 5 mW; field modulation frequency, 13.5 kHz; field modulation amplitude, 1.5 Gauss; time constant, 0.1 s; sweep width, 10 Gauss; scan time, 8 s; and magnitude of the field gradient, 1.7 Gauss/cm. EPR images were reconstructed on 128 × 128 matrix by filtered back-projection using a Shepp-Logan filter. The field of view was 6 × 6 cm.

**MRI scanner and pulse sequences.** MRI measurements were done at 4.7 T controlled with ParaVision 3.0.1 (Bruker BioSpin MRI GmbH, Rheinstetten, Germany). For T₂ mapping, spin echo images were obtained using a multislice multiecho sequence with repetition time of 4,000 ms and a 16 echo train with 15-ms echo times. The scan time for a T₂ mapping image set (NEX = 1) by the multislice multiecho sequence was 5 minutes. The spoiled gradient echo (also referred as gradient echo fast imaging; repetition time, 75 ms; echo time, 3 ms; flip angle, 45 degrees; NEX = 2) was employed for the acquisition of T₁-weighted images. The scan time for an image set (which included two slices) by the spoiled gradient echo sequence was 20 s. Other image variables are as follows: image resolution of phase encoding dimension, 256; gradient encoding dimension, 130; field of view, 3.2 × 3.2 cm; pixel resolution, 256 × 256; and slice thickness, 2.0 mm.

**In vivo MRI experiments.** Mice were anesthetized and secured on a special mouse holder by adhesive skin tape, stomach side down. The tail vein was cannulated for the injection of 3CP. Then, the mouse was placed in the resonator, which was previously warmed up by hot water cycling pad. The resonator unit including the mouse was placed in the 4.7-T magnet. MR measurements were started after the mouse body temperature came up to 37°C. Before the experiments, multislice multiecho–based T₂ mapping was done. The spoiled gradient echo–based T₁ enhanced image data sets were repeatedly scanned for 10 minutes. The contrast agent 3CP was injected (1.5 μmol/g b.w.) via the tail vein cannula 2 minutes after starting the scans.

**Image analysis.** The EPR imaging and MRI data were analyzed using the ImageJ software package (a public domain Java image processing program inspired by NIH Image that can be extended by plug-ins; http://rsb.info.nih.gov/ij/). T₂ mapping was calculated using a plug-in (MRI analysis calculator, Karl Schmidt, HypX Laboratory, Brigham and Women’s Hospital) available in ImageJ.

**Statistical analyses.** The statistical differences were estimated with TTEST function in the Microsoft Excel XP. The suitable “type” and “tail” for the test was selected according to the correspondence and variance of the data. Significance were estimated when P < 0.05.

**Results**

To compare and contrast the capabilities of EPR imaging and MRI in monitoring the time-dependent change in image intensity in solutions where the nitroxide is converted to the corresponding hydroxylamine, phantom experiments with 3CP in the presence of ascorbic acid were conducted. Figure 1 shows the reduction of 3CP by ascorbic acid monitored by EPR imaging (A and B) and T₁-weighted spoiled gradient echo MRI (C and D). The image matrix was 128 × 128 for EPR imaging and 256 × 256 for MRI. The field of view is 3.2 × 3.2 cm in both experiments. A region of interest (ROI) consisting of a 1.1-cm circle corresponding to 1,597 pixels for EPR imaging and 6,668 pixels for MRI was selected. Semilogarithmic plots of the time course of average EPR signal intensity and MRI signal change in the ROI are shown below the corresponding images (Fig. 1B and D). Decay rate constants were obtained from the slope of the linear portion of the decay curves. Both EPR imaging and MRI showed similar reduction rates of image intensity, which in turn reflects nitroxide levels. This result shows that, using the T₁ contrast capability of nitroxides, it is possible to monitor time-dependent changes in image intensity. The good agreement of the reduction rates of image intensity between EPR imaging and MRI suggests that MRI may have advantages over EPR imaging with respect to both spatial and temporal resolutions in following the time-dependent changes in nitroxide levels.

A schematic drawing of the geometry of the mouse and the resonator is shown in Fig. 2A. Figure 2A shows the schematic arrangement of the two legs of the mouse in the resonator with orientation with the magnetic field and the view of a two-dimensional EPR image. Figure 2B shows a time course of two-dimensional spatial images of nitroxide probes obtained by CW EPR imaging after an i.v. injection of 3CP. The image in Fig. 2B (bottom row, extreme right) is a display of maximum intensity image (6.4 minutes) with 33% dynamic range, which was used to select ROIs. A contour of the mouse legs was chosen on this image, and then ROI-1 for normal leg and ROI-2 for tumor-bearing leg were selected. The image intensities of both legs were found to decrease with time. However, information related to anatomic structures of mouse legs could not be obtained by EPR imaging. The blur in the EPR image is due to broad line width of the nitroxide (1.2 Gauss) compared with the scan width (10 Gauss). Line width deconvolution was not applied because the deconvolution technique may introduce artifacts in intensity for reliable quantification. The semilogarithmic values of the averaged image intensities in the ROIs were plotted as a function of time after injection of the probe (Fig. 2C). Over the time course, image intensity increased to a maximum value and subsequently decreased with time in both the normal leg and tumor-bearing leg. A decay rate was obtained from the linear part after maximal image intensity was achieved using the least squares method and summarized in the Table 1. It was also found that the normal leg intensity (650 ± 99, n = 3) was significantly smaller than that in the tumor-bearing leg (1,175 ± 168, n = 3) when the values were analyzed by paired t test with two-tailed comparison (P < 0.05). The pixel-based reduction rates of the nitroxide 3CP were computed and the corresponding image displayed in Fig. 2D.

Figure 3A shows the schematic arrangement of the tumor-bearing mouse in the resonator and the slices selected for MRI experiments. An axial slice including the center part of tumor was selected from the scout images. A total of 60 spoiled gradient echo images were obtained during the 20 minutes scan. Therefore, one image was obtained every 20 seconds. The

<p>| Table 1. Decay constant of nitroxide radical by means of EPR spectroscopy, EPR imaging, and MRI |
|----------------------------------------------------------|---------------------------------------------|</p>
<table>
<thead>
<tr>
<th>Normal leg</th>
<th>Tumor leg</th>
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<tr>
<td><strong>n</strong></td>
<td><strong>Decay rate (min⁻¹)</strong></td>
</tr>
<tr>
<td>EPR imaging</td>
<td>3</td>
</tr>
<tr>
<td>MRI</td>
<td>3</td>
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NOTE: Values are indicated as mean ± SD, n, number of experiments. *P < 0.05, between the normal leg and the tumor leg (paired t-test with two-tailed comparison).
initial six images (obtained before injection) were averaged. Then, each subsequent image was divided by the averaged baseline image, multiplied by 100, and finally subtracted by 100 to obtain percent difference ($D\%$).

$$D\%_{i,m,n} = S_{i,m,n}/(\sum_{i=1}^{6} (S_{i,m,n})/6) \times 100 - 100$$  \hspace{1cm} (1)

where $i$ is number of data set, $m$ and $n$ is image matrix, and $S$ is pixel intensity. Spoiled gradient echo–based $T_1$-weighted images showed increasing intensity after administration of 3CP (Fig. 3B). The image (bottom row, extreme right) in Fig. 3B shows the $T_2$ map of the same slice calculated from previously obtained multislice multiecho images. The regions of interest ROI-1 and ROI-2 were chosen based on the $T_2$ map for normal and tumor legs, respectively. The spoiled gradient echo image intensity exhibited an immediate increase by nearly 30%, after which a gradual decrease was noted. Figure 3C shows semilogarithmic plots of the averaged percent difference in the ROI-1 and ROI-2. The normal tissue exhibited a slight delay to reach maximum intensity. The image obtained 0.5 minute after injection showed signal increase only in tumor tissue. However, the image obtained 1.8 minutes after injection showed similar signal level in both the tumor and normal tissues. Maximum enhancements in the tumor ($28.7 \pm 6.9, n = 3$) and normal ($27.3 \pm 8.5, n = 3$) tissues were of similar level. Decay constants in the ROIs were obtained by the least squares method and
summarized in Table 1. From these results, it can be seen that the decay rate in the tumor leg was significantly faster than the normal leg, in agreement with the results obtained from EPR imaging experiments. The pixel-wise reduction rates of nitroxide 3CP were computed and overlaid on a scout multislice multiecho image (Fig. 3D). The MR-based redox mapping shows clear difference of decay rates of 3CP between tumor and neighboring normal tissues.

Figure 4 showed a time course of total (nitroxyl radical + hydroxylamine) amount of 3CP in the normal (■) and the tumor tissues (○) after the i.v. injection. Points, mean from three mice; bars, SD. Each tissue from a mouse was measured by a triplicate experiment. The solid and dotted lines in the figure were obtained by least square method for the values of normal and tumor tissue, respectively.

Discussion

For the past several years, nitroxides have been exclusively used in EPR imaging redox imaging; however, the results of the present study now expand their application as functional redox-sensitive contrast agents for MRI. The significant enhancement in image intensity induced by 3CP administration and the superior temporal and spatial resolution of MRI modality suggest that it is advantageous to monitor the pharmacokinetic distribution of nitroxides using T1-weighted MRI compared with EPR imaging. The major advantages of using nitroxides in MRI as opposed to EPR imaging include the availability of MRI scanners (both for human and small animal studies), multislice imaging capability, enhanced spatial and temporal resolution, and coregistration of images of tissue redox status with anatomic information inherently available from MRI.

Results shown in Fig. 4 suggest that the decreasing intensity of EPR imaging and MRI was due to the reduction of nitroxyl radical rather than clearance. Nitroxides, having a single unpaired electron, can undergo redox transformations between the one-electron oxidized state, the oxoammonium cation, and the one-electron reduced hydroxylamine (Fig. 5). The oxoammonium/nitroxide redox pair constitutes an effective redox couple and supports catalytic activities such as superoxide dismutase mimetic activity and catalase activity (13, 14), which may underlie its protective effects in cells and tissues subject to oxidative damage (15). Although the nitroxide/hydroxylamine pair is not capable of supporting these catalytic processes, it is actively involved in protective activities by scavenging reactive oxygen species. Nitroxide free radicals also participate in radical-radical recombination reactions avidly and thus can neutralize reactive oxygen species (21). The hydroxylamines, on the other hand, can function as conventional H-atom donors such as ascorbate and scavenge free radicals by H-atom transfer (30). The oxoammonium cation can be reduced by one- or two-electron steps to the corresponding nitroxide or hydroxylamine, respectively (12–14). Nitroxides provide protection in cells and tissues against diverse types of insult, such as exposure to superoxide and hydrogen peroxide, by directly scavenging the ROS (31). In addition to protection by radical scavenging, nitroxides also evoke cellular responses such as cell signaling—specific pathways (32, 33). The ability to trigger cell signaling—specific pathways has been postulated to support possible antitumor effects of nitroxides in vivo (34, 35). When nitroxides are incubated with cells or administered in vivo, a dynamic equilibrium is established between the nitroxides and hydroxylamines (29, 36, 37). The equilibrium levels of these species are dependent on tissue oxygenation and the levels of reducing equivalents or the tissue “redox status” (18, 38).

The therapeutic effects of nitroxides have been evaluated in animal models against diverse types of damage or in spontaneously developing pathologic conditions. Nitroxides were found to be effective protectors in various disease models involving free radicals in experimental animals (39). Based on their efficacy as protectors in these studies, they were recently tested in humans (40). Topical application of the nitroxide Tempol was found to be effective in limiting radiation-induced...
alopecia in human scalp, an adverse effect in radiotherapy with free radical involvement. The efficacy of these agents has been attributed to their radical scavenging efficiency and, being low molecular weight compounds, their ability to accumulate at effective concentrations in critical subcellular compartments. Based on these and other ongoing studies, nitroxides may be potential candidates for systemic administration in humans for therapeutic purposes in various pathologic conditions. Therefore, there exists a need to monitor their levels in vivo with currently available clinical imaging modalities.

MRI studies on phantom objects containing the nitroxide 3CP show that it is possible to elicit sufficient $T_1$ contrast enhancement despite their lower relaxivity [$-0.2$ (mmol/L)$^{-1}$ s$^{-1}$] compared with Gd$^{3+}$ complexes [4 (mmol/L)$^{-1}$ s$^{-1}$]. One advantage of the lower relaxivity of nitroxides in MRI is that a linear response between the concentration and intensity enhancement can be expected. It is then possible to quantify by making rapid $T_1$ assessments. In vivo MRI experiments using 3CP at doses well tolerated in mice also show that it is possible to monitor their accumulation and clearance in the tissues/organisms of interest. Recently, the in vivo distribution of spin-trapped nitric oxide using the Fe(H)-chelated N-methyl-D-glucamine dithiocarbamate as a spin-trap agent was obtained by $T_1$-weighted spin-echo MR imaging at 1.5 T (41).

The biological instability of nitroxide free radicals, which was a major limitation as a $T_1$ contrast agent in providing sufficient image intensity enhancement in earlier studies, can now be exploited to report on tissue redox status. This will be possible provided that the clearance of the agent and its metabolite is not the major contributor to the observed time-dependent decrease in image intensity resulting from $T_1$ contrast. Ex vivo analyses of nitroxides and hydroxylamines after in vivo administration of 3CP in tumor-bearing mice show that within the time window, the levels of (nitroxide +hydroxylamine) are practically invariant whereas the nitroxide levels decrease (29, 36, 37). Thus, the change in the image intensity in MRI as a function of time can be attributed predominantly to nitroxide reduction. The nitroxide reduction rates, which depend on tissue redox status, were found to be higher in tumor compared with muscle by both EPR imaging and MRI. As first noted by Swartz et al. (25) and Berliner et al. (6), nitroxides have the capability to serve as hypoxia-sensitive contrast agents whereas hydroxylamines can serve as oxygen-sensitive pro-contrast agents (42). Monitoring profiles of reduction/oxidation of nitroxide/hydroxylamines in normoxic/hypoxic tissue may actually serve as a viable approach to assess the global redox status in tissue using EPR imaging or MRI. The pharmacokinetics of nitroxide spin probe can be obtained using either EPR imaging or MRI. Although EPR imaging can detect nitroxide free radicals itself directly and obtain images of nitroxide free radical distribution as well as redox maps, the poor image resolution and lack of anatomic detail limit its use in the clinical setting presently. On the other hand, the $T_1$-weighted MRI serves as an indirect detection modality of nitroxide contrast agents. The $T_1$-weighted spoiled gradient echo–based dynamic MRI can give appropriate tumor redox status information with useful anatomic resolution. Such capabilities may be clinically useful when nitroxides are used as radioprotectors of surrounding normal tissue while delivering therapeutic doses of radiation to tumors. MRI studies with nitroxides could be potentially used to optimize treatment schedules based on the maximal possible difference of nitroxide levels in normal and tumor regions.

References

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