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Hepatic Arterial Embolization with Doxorubicin-Loaded Superabsorbent Polymer Microspheres in an Animal Model

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Abstract

Objectives—To study the pharmacokinetic profile after hepatic arterial embolization with superabsorbent microspheres (QuadraSpheres) loaded with doxorubicin.

Materials and Methods—Rabbits with hepatic VX2 tumors were treated with intra-arterial administration of QuadraSpheres loaded with doxorubicin, or transarterial chemoembolization (TACE) using doxorubicin, Lipiodol and Embospheres, or hepatic arterial infusion (HAI) of doxorubicin. Tumor specimens were evaluated by fluorescence microscopy, and plasma and tumor concentrations of doxorubicin were measured.

Results—The peak plasma concentration of doxorubicin was lower in the QuadraSphere group (309.9 ng/ml) than in the HAI (673.4 ng/ml) or TACE (360.5 ng/ml) groups, suggesting higher tumor retention in the QuadraSphere group. Intratumoral doxorubicin levels declined to negligible levels at 1 and 3 days after treatment, respectively in the HAI and TACE groups. In the QuadraSphere groups, intratumoral doxorubicin level declined after day 1, but was still detectable at 14 days after treatment and was higher than that in the other groups at 1, 3, and 7 days. Intratumoral doxorubicin fluorescence was detected at all time points in the QuadraSphere group, but only at 1 day after treatment in the TACE group.

Conclusions—Hepatic arterial administration of doxorubicin-loaded QuadraSpheres enables the sustained release of doxorubicin to hepatic tumors.

Keywords

Hepatic artery embolization; Drug-eluting microspheres; Pharmacokinetics

Introduction

Treating patients with primary or secondary liver malignancies is challenging. Surgery, the only potentially curative therapeutic option, is possible in only 5%–20% of patients (1-5), and systemic chemotherapy generally has had only limited success in liver metastasis or

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hepatocellular carcinoma. Furthermore, patients who receive systemic chemotherapy can develop serious adverse effects. Because of the high risk of morbidity and death associated with a large tumor burden in the liver, alternative techniques based on regional delivery of chemotherapy to the liver are being used increasingly for cytoreductive or palliative purposes.

The aim of hepatic arterial infusion (HAI) of chemotherapy is to increase drug delivery to hepatic tumors while minimizing undesirable systemic toxic effects. Transarterial chemoembolization (TACE) combines regional chemotherapy and embolization to increase the time of exposure to cytotoxic agents and induce ischemia in the tumor. TACE offers a survival benefit to patients with intermediate hepatocellular carcinoma (6, 7). Although using combinations of embolic agents and iodized oil in standard TACE therapy can potentially slow the washout of the cytotoxic agent from the tumor, the drug is still rapidly released from the iodized oil solution.

One relatively new strategy for increasing the effectiveness of regional chemotherapy is the use of drug-eluting microspheres that enable the prolonged release of a chemotherapeutic agent into a tumor (8-16). A sustained drug concentration within the tumor bed has been shown to increase the probability of cell death (17-19). A few recent animal and clinical studies have shown that drug-eluting microspheres can be used to deliver doxorubicin to a tumor site over an extended period while minimizing the systemic release of the drug (8-16).

QuadraSpheres, a new type of nonbiodegradable, superabsorbent polymer microsphere (BioSphere Medical Inc., Rockland, MA), absorb fluid and swell when exposed to aqueous media (20). These particles differ from previous embolic agents and drug-eluting beads in that they are soft and deformable and conform to the lumen of the embolized vessels (20-22). Hori and his colleagues first reported the successful utilization of these microspheres (23). Superabsorbent polymer microspheres have been used clinically in humans to embolize large hepatocellular carcinomas (24); in addition, in vitro studies have suggested that these microspheres can absorb several chemotherapeutic drugs that can be released from the microspheres at variable rates (25, 26). A recently published study showed that after intra-arterial administration of doxorubicin-loaded superabsorbent polymer microspheres in an animal model, intra-tumoral doxorubicin concentration peaked at 3 days and remained detectable till 7 days (26). However, to the best of our knowledge, no previous study has compared the pharmacokinetics between drug-loaded QuadraSpheres, TACE, and HAI. In this study, we evaluated the pharmacokinetic profile after hepatic arterial embolization with superabsorbent polymer microspheres loaded with doxorubicin in a rabbit liver tumor model and compare this technique with that of HAI of doxorubicin and standard TACE with iodized oil and tris-acryl gelatin microspheres (Embospheres).

Materials and Methods

Animals

All experiments involving New Zealand white rabbits were approved by the Institutional Animal Care and Use Committee at our institution. Animals were maintained in facilities approved by the Association for Assessment and Accreditation of Laboratory Animal Care

International and in accordance with current U.S. Department of Agriculture, Department of Health and Human Services, and National Institutes of Health regulations and standards.

Tumor Model

The rabbit VX2 carcinoma was used for the study. Although this tumor is not human in origin, it was selected for several reasons. It is a highly malignant carcinoma that has both squamous and adenomatous characteristics. It grows rapidly at the inoculation site and metastasizes to regional lymph nodes and lungs (27, 28). It possesses characteristics similar to those of human carcinomas, including heparin-dependent angiogenesis (27, 28), a biochemical phenotype characteristic of advanced-stage liver tumors (i.e., high glycolysis and elevated levels of mitochondrial-bound hexokinase) (27, 29), and a lack of spontaneous regression. In addition, when rabbit VX2 carcinoma is implanted in the liver, its blood supply (hepatic artery and portal vein) is similar to that of human liver tumors; lipiodol has been shown to selectively accumulate and remain in the tumor after intra-arterial administration (30-32). Furthermore, the tumor can be readily identified by angiography, and the rabbit vasculature is large enough to allow selective hepatic arterial catheterization.

Tumor Inoculation

Single VX2 tumors were inoculated into the liver in 65 male New Zealand white rabbits (3.5–4.2 kg) in the following manner. Each rabbit was sedated with an intramuscular injection of buprenorphine (0.15 mg; Bedford Laboratories, Bedford, OH), and anesthesia was induced with 5% isoflurane/oxygen (1.5 L/min) administered via mask and maintained with 3%–5% isoflurane/oxygen (1.5 L/min). Enrofloxacin antibiotic (Baytril; Bayer Corporation, Agriculture Division, Animal Health, Shawnee Mission, KS) was given intramuscularly at a dose of 5.0 mg/kg. The abdomen was shaved and prepared for aseptic surgery. A small midline incision was made, and the left lateral lobe of the liver was exteriorized and inoculated at a single site with 0.3 mL of freshly harvested and prepared VX2 tumor fragments. The fragments were placed in the liver through an 18-gauge needle attached to a 1-mL syringe. Direct inoculation of tumor fragments into a single site in the left lobe allowed the growth of a solitary, well-demarcated tumor in the liver of each recipient rabbit. After hepatic inoculation, the abdomen was closed in layers, and the animal was kept warm and monitored until it recovered from anesthesia. The tumors were allowed to grow in the rabbits' livers for 14–16 days before treatment.

Tumor Treatment

At the time of treatment, each animal was anesthetized with a 150-mg intramuscular injection of ketamine (Fort Dodge Animal Health, Fort Dodge, IA) and 10 mg of acepromazine (Vedco, Inc., Saint Joseph, MO), and antibiotics were administered as before. A 22-gauge intravenous catheter (Insyle™ Autogard™ Winged; Becton Dickinson Therapy Systems Inc., Sandy, UT) was placed in a marginal ear vein, and anesthesia was maintained with use of intravenous injections of 25 mg/mL of thiopental sodium (pentothal; Hospira, Inc., Lake Forest, IL) given to effect.

The right groin was shaved and prepared for aseptic surgery. The right femoral artery was isolated via a cut down, a 4.0 Fr introducer sheath (Cook Inc., Bloomington, IN) was placed

in the artery through a small arteriotomy, and heparin sodium (100 IU/kg) was administered. A 2.8 Fr microcatheter (EmboCath Plus; BioSphere Medical, Rockland, MA) was inserted through the sheath in the femoral artery. With the help of a 0.014-in. hydrophilic guidewire (Transend; Boston Scientific, Miami, FL), the microcatheter was advanced up the aorta, and manipulated into the celiac axis under fluoroscopic monitoring. A digital subtraction arteriogram was obtained by hand-injecting approximately 3.0 mL of radiographic contrast medium (Conray® 60; Mallinckrodt Inc., St. Louis, MO) and using serial x-ray filming to document the location and size of the tumor and to delineate its blood supply. The catheter was then manipulated into the proper hepatic artery and positioned distal to the origin of the gastroduodenal artery. Blood flow around the catheter and the absence of arterial spasm were verified by hand-injection of the contrast/saline mixture.

Treatment Groups

Twenty rabbits were treated with HAI of 4.0 mg of doxorubicin dissolved in 2 mL solution containing 1 ml of nonionic contrast medium (Visipaque 320; GE Healthcare, Inc., Princeton, NJ) and 1mL of saline (the *HAI group*). Another 20 rabbits were treated with hepatic arterial administration of 4.0 mg of doxorubicin mixed with 0.4 mL of Lipiodol (Ethiodol; Savage Laboratories, Melville, NY), followed by embolization with 100- to 300- μ m tris-acryl gelatin microspheres (Embospheres; BioSphere Medical Inc., Rockland, MA) until stasis was achieved (the *TACE group*). A third group, containing 25 rabbits, was treated with hepatic arterial administration of 50- to 100- μ m superabsorbent polymer microspheres loaded with 4.0 mg of doxorubicin (the *QuadraSphere group*). Hepatic arterial administration of respective materials in each treatment group was performed under continuous fluoroscopic monitoring to avoid any reflux into the gastroduodenal or gastric arteries.

The doxorubicin-QuadraSphere mixture was prepared by adding 15 mL of nonionic contrast medium (Visipaque 320; GE Healthcare, Inc., Princeton, NJ) to 50 mg of doxorubicin powder (Bedford Laboratories) and adding 10 mL of saline to 25 mg of 50- to 100- μ m QuadraSpheres. After the doxorubicin powder dissolved completely (about 15 minutes), full aliquots of both solutions were drawn into a 30-mL syringe. After 2–4 hours, 2.0 mL of the mixture (containing 4.0 mg of doxorubicin and 2.0 mg of QuadraSpheres) was injected into each rabbit. After treatment, the catheter and sheath were removed, the femoral artery was ligated, and the incision was closed in two layers with 4-0 Vicryl.

Pharmacokinetics

Blood was collected immediately before and at 10, 20, 40, 60, 120, and 180 minutes after treatment via a catheter inserted in the ear vein in 5 animals per treatment group. Blood was also collected just before euthanization in animals sacrificed one day after treatment. Doxorubicin and doxorubicinol levels in these blood samples were analyzed with use of liquid chromatography-mass spectrometry. Blood samples were also collected to determine liver function at 1 hour after treatment and just before euthanization in 5 animals per treatment group.

Euthanasia, Necropsy, Tissue Preparation, Histologic Analysis, and Light and Fluorescence Microscopic Analyses

Rabbits were euthanized with an intravenous overdose of Beuthanasia-D (70 mg/kg; Schering-Plough Animal Health Corp., Kenilworth, NJ), and a complete necropsy was performed at 1 hour and at 1, 3, or 7 days after treatment in the HAI and TACE groups and at 1 hour and at 1, 3, 7, or 14 days after treatment in the QuadraSphere group (5 animals at each time point in each treatment group). The liver tumors were removed and divided into two halves. One half was formalin-fixed for subsequent light and fluorescence microscopic examinations, and the other half was submitted for doxorubicin analysis.

After tumor fixation, liver and tumor tissue specimens from rabbits in the TACE and QuadraSphere groups were trimmed into a series of 2- to 3-mm-thick histologic blocks that were embedded in paraffin, cut at nominal 5- μ m intervals, and mounted on slides. The slides were either stained with hematoxylin and eosin (H&E) for light microscopic examination or left unstained for fluorescence microscopic examination. An experienced veterinary pathologist (C.S.V.P.) evaluated all histologic slides for the presence, size, and morphologic features of QuadraSpheres and Embospheres, the number of spheres in each vessel, and presence of perivascular inflammation. However, because VX2 tumors spontaneously necrose, we did not compare the two groups in terms of degrees of necrosis. As a pre-examination control, empty and doxorubicin-loaded QuadraSphere aliquots were placed on lens paper (Fisher Scientific, Plano, TX) in tissue cassettes, processed similarly to the tissues on the H&E slides, and examined under light microscopy for morphologic and staining characteristics.

Fluorescence microscopy was used to visualize the distribution of doxorubicin in tumor tissue. Doxorubicin autofluorescence was detected with use of an Olympus BX51 research microscope (Olympus America Inc, Melville, NY). Images were captured with an Olympus U-MCAD-2 digital camera and were acquired with Magnafire 2.1C digital imaging software (Optronics, Goleta, CA). The depth of fluorescence penetration at the edge of the microspheres was measured by using Image-Pro Plus image analysis software (Media Cybernetics, Inc. Silver Spring, MD).

Statistical Analysis

For the plasma and tissue drug concentration data, differences in average drug concentration were assessed within each time point using a one-way analysis of variance model (ANOVA). Pairwise comparisons were accomplished using Gabriel's multiple-comparison procedure. The peak AST and ALT levels were compared between the QuadraSpheres and TACE treatment groups using the Satterthwaite's approximate two-sample two-tailed t-test. All analyses were conducted using the SAS software package (SAS Release 9.1.3. 2002, SAS Institute: Cary, NC). A p-value less than 0.05 was considered statistically significant.

Results

Plasma and Tissue Pharmacokinetics

The plasma doxorubicin concentration peaked at 10 minutes in all treatment groups, returned to near baseline at about 60 minutes, and stayed low until 24 hours after the procedure (Fig 1A). The peak plasma levels of doxorubicin in the QuadraSphere group were significantly lower than those in the HAI group (309.9 ng/ml versus 673.4 ng/mL; $p = 0.0183$). Although the plasma concentrations of doxorubicin in the QuadraSphere group were lower than those in the HAI group at 20, 40, and 60 minutes, these differences were not statistically significant; similarly, plasma doxorubicin levels in the QuadraSphere group were lower than those in the TACE group at all time points; but this was not statistically significant. The plasma doxorubicin concentration in the HAI and TACE groups peaked at 10 and 60 minutes, respectively, followed by a steady decline (Fig 1B). In contrast, the pharmacokinetic profile after treatment with QuadraSpheres showed constant plasma doxorubicin concentrations, starting at 10 minutes after administration and lasting until the final measurement was taken (24 hours after administration).

In the HAI group, the mean intratumoral doxorubicin levels were highest (153.4 ± 211.2 ng/mg) in animals euthanized 1 hour after the procedure and sharply declined to negligible levels (17.1 ± 13.2 ng/mg) within 1 day after treatment (Fig 2). In the TACE group, intratumoral doxorubicin levels were similar at 1 hour (61.9 ± 41.9 ng/mg) and 1 day (61 ± 34.9 ng/mg) after treatment and declined to minimal levels within 3 days (22.9 ± 12.1 ng/mg). In the QuadraSphere group, the greatest level of intratumoral doxorubicin (196.5 ± 312.8 ng/mg) was seen at 1 day after treatment. The levels gradually declined after that, but substantial amounts (43.88 ± 23.2 ng/mg) were still detectable at 14 days after treatment. The mean intratumoral doxorubicin concentrations in the QuadraSphere group were higher than those in the other two groups at 1, 3, and 7 days after treatment. The differences in the mean tumor doxorubicin concentrations among the three delivery methods were statistically significant at 3 ($p=0.0065$) and 7-days ($p = 0.0230$). Gabriel's pairwise comparison analysis showed that at 3 days after treatment, the mean intratumoral doxorubicin concentrations in the QuadraSphere group was significantly higher than the other 2 groups, whereas the differences between the TACE and HAI groups were not statistically significant.

Histologic Features of Microspheres

QuadraSpheres and Embospheres were found in intratumoral and peritumoral vessels, and variable degrees of microsphere-associated transmural and perivascular inflammation occurred at all time points. The inflammatory reaction was similar in the 2 groups and mainly composed of neutrophils, macrophages, and multinucleated giant cells. QuadraSpheres were deformed and conformed to the vessel lumen and adjacent particles, whereas Embospheres retained their spherical shape (Fig 3C). QuadraSpheres ranged from 165 to 475 μm , Embospheres from 98 to 283 μm . The number of QuadraSpheres in each embolized vessel ranged from 1 to 12, with a mean of 3.1; 31 of the 50 embolized vessels with microspheres (62%) contained more than one microsphere.

In the in vitro experiments, the empty QuadraSpheres were basophilic, whereas the doxorubicin-loaded QuadraSpheres were eosinophilic. In tumor tissue, most of the QuadraSpheres were eosinophilic with occasional clefts; however, a few of the QuadraSpheres were basophilic (Fig 3B). The Embospheres in tumor tissue were round and eosinophilic with occasional basophilic rims (Fig 3C). The size and morphologic features of the QuadraSpheres did not vary at different intervals after treatment. However, animals euthanized 14 days after treatment had more basophilic QuadraSpheres (28.6%) than did those euthanized at 1, 3, or 7 days after treatment (0%, 7.8%, and 4.6%, respectively). The size, morphologic features, and staining characteristics of the Embospheres did not vary at different intervals after treatment.

Doxorubicin Fluorescence

Animals that were euthanized 1 day after treatment in both the QuadraSphere and TACE groups showed intratumoral doxorubicin fluorescence (Fig 4 and 5, respectively). In the QuadraSphere group, fluorescence was concentrated around the microspheres and extended 400–1600 μm into the surrounding tumor tissue (Fig 4). In the TACE group, however, doxorubicin fluorescence was randomly distributed throughout the tumor and surrounding normal liver tissue. In the QuadraSphere group, rabbits euthanized at 3, 7, or 14 days after treatment showed intratumoral doxorubicin fluorescence; the fluorescence distribution and intensity were similar to those in rabbits euthanized 1 day after treatment (Fig 4). In comparison, minimal or no fluorescence was detected in the TACE group animals euthanized 3 or 7 days after treatment (Fig 5), even with exposure times that were 9 or 10 times longer than those used for animals in the QuadraSphere group.

Liver Function Tests

In the HAI group, no appreciable changes were seen in the serum levels of aspartate aminotransferase (AST), alanine aminotransferase (ALT), and alkaline phosphatase after treatment. Rabbits in the TACE group showed transient elevation in AST and ALT levels after treatment, reaching peak concentration at 1 day after treatment. AST levels returned to baseline within 3 days after treatment, and ALT levels within 7 days after treatment. In the QuadraSphere group, the AST levels peaked at 1 day after treatment and then gradually returned to baseline within 14 days after treatment. The ALT levels in this group also increased sharply within 1 day after treatment, continued to increase until 7 days after treatment, and then returned to baseline within 14 days after treatment. The peak AST levels in the QuadraSphere group were lower than those in the TACE group ($p=0.0251$); although the peak ALT levels were also lower, this difference did not reach statistical significance ($p=0.1177$). Serum bilirubin levels remained normal at all time points in all three groups.

Discussion

Results of the current study suggest that hepatic arterial administration of doxorubicin-loaded QuadraSpheres results in the sustained release of doxorubicin to hepatic tumors. The plasma doxorubicin pharmacokinetic profile after HAI in the current study is in keeping with earlier studies that showed that although HAI allows drugs to be delivered to liver tumors at higher doses than those delivered in systemic administration, very little of the drug

is retained in the tumor. The use of Lipiodol during standard TACE has been shown to promote drug retention in tumors (33-36). Similar to the results of the current study, Nakamura et al. (37) showed that after administering an emulsion of an anticancer drug and Lipiodol, the level of the anticancer drug in the blood was markedly lower than that after an arterial infusion of an identical dose of the drugs alone; however, in their study, the sustained release of the emulsion was serially measured for only 30 minutes. In an in vitro elution study, Lewis et al. (13) found that a Lipiodol suspension that rapidly released doxorubicin had a half-life of approximately 1 hour.

The temporal pharmacokinetic profile of serum doxorubicin levels after TACE in the present study, namely peak concentrations at 10 minutes after treatment with return to near baseline levels at 60 minutes after treatment, is in keeping with the above-mentioned results. Although the tumor doxorubicin levels in the TACE group remained high at 1 hour and 1 day after treatment, they sharply declined to minimal levels at 3 days after treatment, suggesting rapid elution of doxorubicin from the tumor. This finding is further corroborated by the finding that although animals killed 1 day after TACE showed tumor fluorescence, none of the animals killed 3 or 7 days after TACE had appreciable tumor fluorescence, suggesting that very little drug remained in the tumors at these times. On the basis of these results, we believe that although the use of standard TACE with Lipiodol allows greater tumor doxorubicin deposition than the use of HAI allows, TACE plus Lipiodol does not prolong doxorubicin retention in the tumor for more than 24 hours after treatment.

The lower plasma doxorubicin concentrations in the QuadraSphere group compared with other treatment groups, as seen in the current study, demonstrate higher tumor retention of the drug in the animals treated with QuadraSpheres. Lower plasma doxorubicin levels in the QuadraSphere group also has the potential benefit of reducing systemic exposure to the chemotherapeutic drug, which in turn could allow administration of higher concentrations of doxorubicin to the tumor. The pharmacokinetic profile of plasma doxorubicin in the QuadraSphere group, i.e., sustained levels from 10 minutes until 24 hours after treatment, also favors the slow drug-release feature of the QuadraSpheres. These results are in keeping with those reported by Lee et al (26), who found a sustained plasma doxorubicin levels between 20 minutes to 120 minutes after hepatic arterial administration of doxorubicin-loaded QuadraSpheres. In the same study, Lee et al (26) found that doxorubicin concentration in the tumor peaked at 3 days and remained detectable till 7 days; however, unlike the current study, Lee et al did not evaluate the pharmacokinetic profile after HAI or standard TACE. In our study, we found that in contrast to the HAI and TACE treatment groups, animals treated with QuadraSpheres showed high intratumoral levels of doxorubicin until 14 days after treatment; these findings suggest that hepatic arterial administration of QuadraSpheres results in prolonged drug retention in the tumor. The prolonged, sustained drug-release property of QuadraSpheres is further illustrated by the presence of persistent fluorescence around the microspheres 14 days after treatment. Fluorescence microscopy also allowed us to study the spatial drug distribution, demonstrating that doxorubicin released from the microspheres extended 400-1600 μm into the surrounding tissues.

Because sustained drug release increases the possibility of tumor cell death (17-19, 38), the findings suggest that treating liver tumors with doxorubicin-loaded QuadraSpheres has

potentially higher therapeutic efficacy than does standard TACE or HAI. Also, the decreased release of the drug into the systemic circulation may reduce the systemic toxicities associated with the chemotherapeutic agent.

We found that QuadraSpheres deform to conform to the morphology of the vessel lumen and adjacent particles, leaving virtually no space in the occluded vessel. The tendency of QuadraSpheres to swell and conform to the vessel wall without leaving spaces may lead to more complete occlusion of the vessels compared with the spherical particles that tend to maintain their shape. This finding is consistent with previous studies' results (20-22). Another study also found that QuadraSpheres had a higher in vivo deformation rate (15%) than Embospheres did (9%); the study's authors concluded that this difference may have been attributable to the different mechanical properties of the two types of microspheres in terms of surface structure, absorption ability, and deformability (22). In the current study, the size of QuadraSpheres in the tissue specimens ranged from 165 to 475 μm , approximately 3.5–4 times larger than the particles in their dry state (50–100 μm). Previous in vitro and in vivo studies have shown similar swelling characteristics for these particles (20, 22, 24, 39, 40).

Similar to previous reports, we found that Embospheres had an eosinophilic appearance (20, 41). However, unlike a previous study (20) that showed that QuadraSpheres are basophilic, most QuadraSpheres in the present study were eosinophilic on H&E staining. We believe that this eosinophilic appearance of the QuadraSpheres was due to the presence of doxorubicin within the microspheres. This was confirmed by our in vitro experiments, which showed that the empty QuadraSpheres were basophilic, whereas the doxorubicin-loaded QuadraSpheres were eosinophilic. The basophilic QuadraSpheres seen in tissue probably had minimal or no doxorubicin, either secondary to incomplete loading or to the release of doxorubicin into the surrounding tissues. The latter is supported by the fact that more basophilic Quadraspheres were found at 14 day time point as compared to earlier time points. However, further in vitro studies are required to definitely show that the change in staining pattern is related to drug elution from the microspheres.

The presence of mild to moderate perivascular inflammation around both Embospheres and QuadraSpheres was probably a foreign body reaction (41). Using a rabbit renal model, Khankan et al. (20) found that rabbits killed 1 week after embolization with QuadraSpheres showed a mild foreign body reaction consisting of macrophages. In another study, de Luis et al. (22) found lymphocytes and giant cells around the microspheres in pigs killed 4 weeks after renal artery embolization with QuadraSpheres. In the current study, the presence of significant perivascular inflammation in rabbits killed 1 day after treatment in the TACE group was in contrast to previous animal studies, in which inflammation was seen only much later. For example, Siskin et al. (42), in a study involving embolization of porcine kidneys, found that inflammatory response increased over time after embolization with EmboSphere and EmboGold microspheres—inflammation was not detectable at 7 days and was highest at 28 days. Derdeyn et al. (43), in an in vivo animal study with Embospheres, found no inflammation at 48 hours but found chronic transmural and perivascular inflammation after 4 weeks. We believe that the early onset of inflammation seen in our TACE group was probably caused by Lipiodol.

One of the major limitations of this study was that we could not compare the different treatment groups in terms of therapeutic efficacy because VX2 tumors have been shown to have varying degrees of spontaneous necrosis, and it was not possible to differentiate treatment-induced necrosis from spontaneous necrosis. In addition, since we did not quantify the fluorescence intensity, the study does not provide any information related to drug concentration gradient in tumor tissue. However, findings from the current study clearly show that compared with HAI and standard TACE, hepatic arterial administration of QuadraSpheres results in prolonged tumor exposure to doxorubicin, which could translate into increased therapeutic efficacy.

Acknowledgments

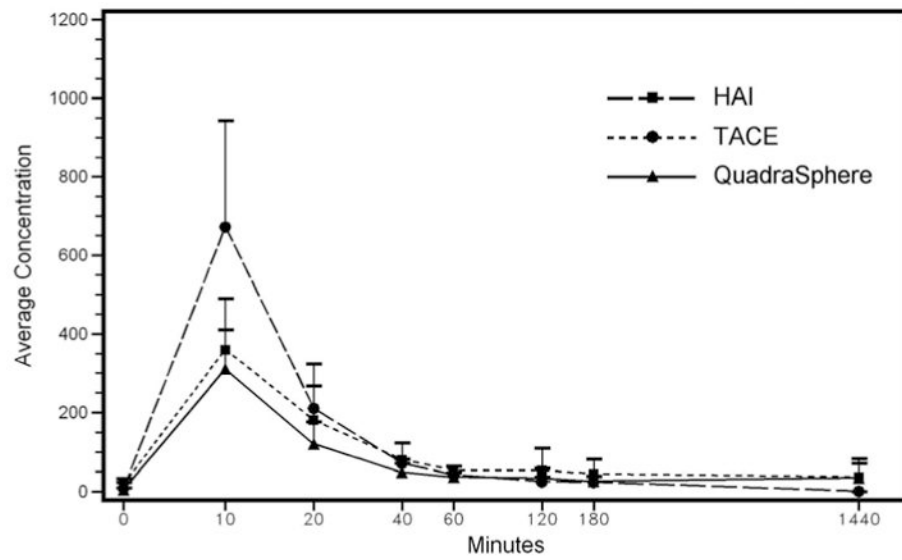
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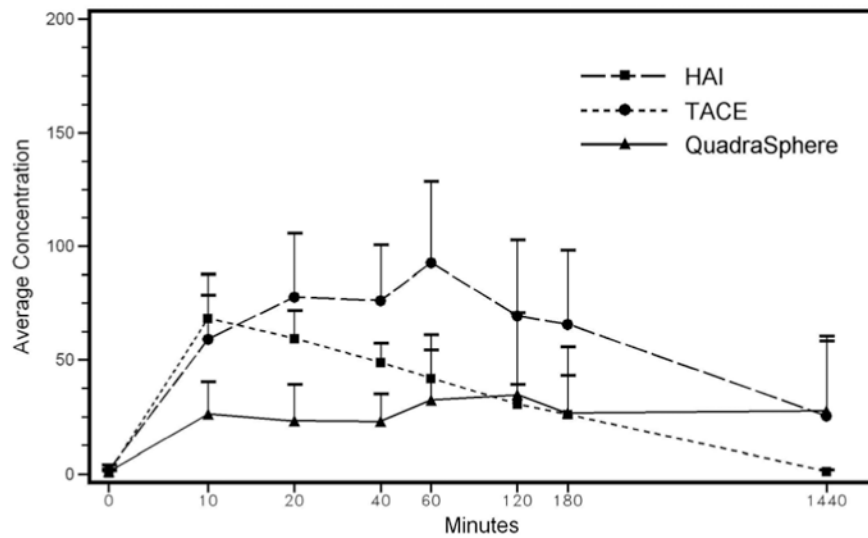
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A.



B

Figure 1.

(A) Serum doxorubicin (ng/ml) and (B) doxorubicinol (ng/ml) levels at various times after treatment in the three treatment groups. The x-axis is on a logarithmic scale to accommodate the 1440 hours time point.

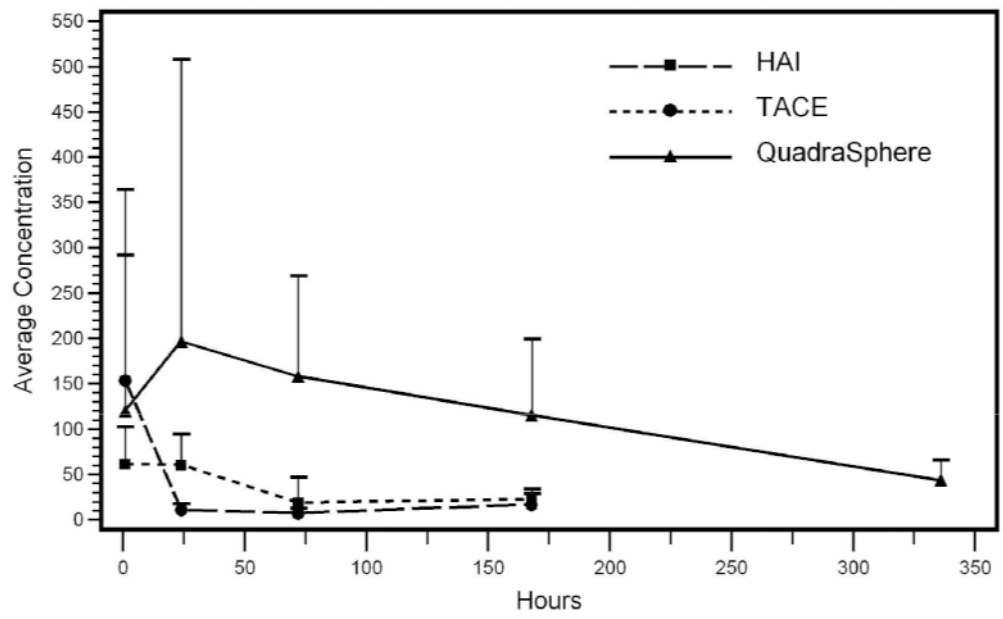
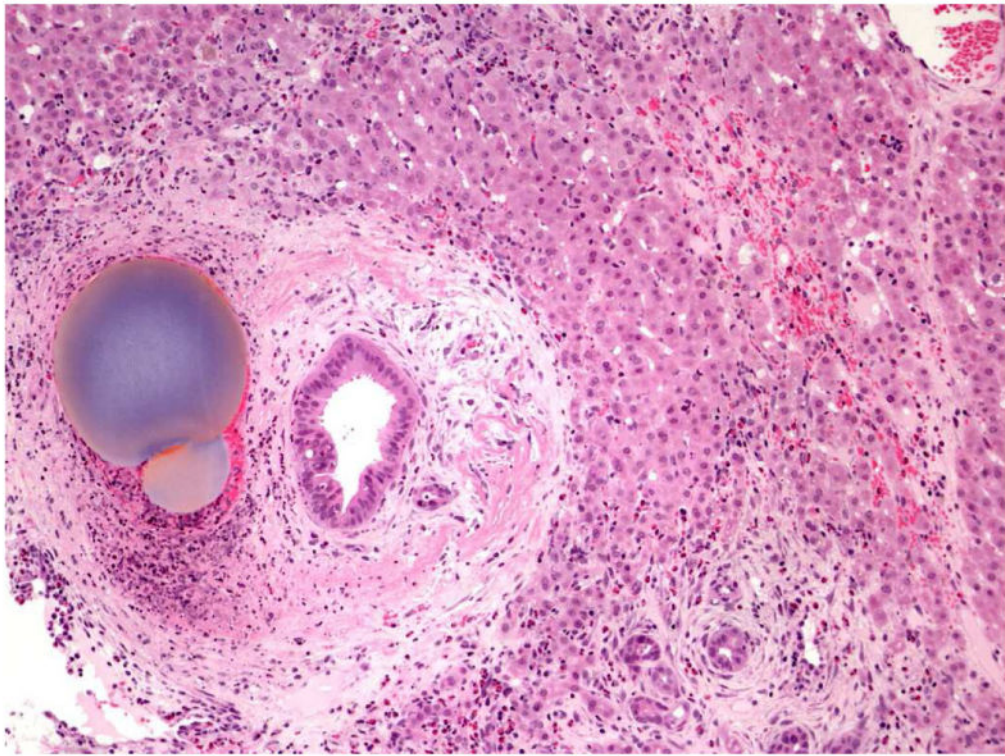


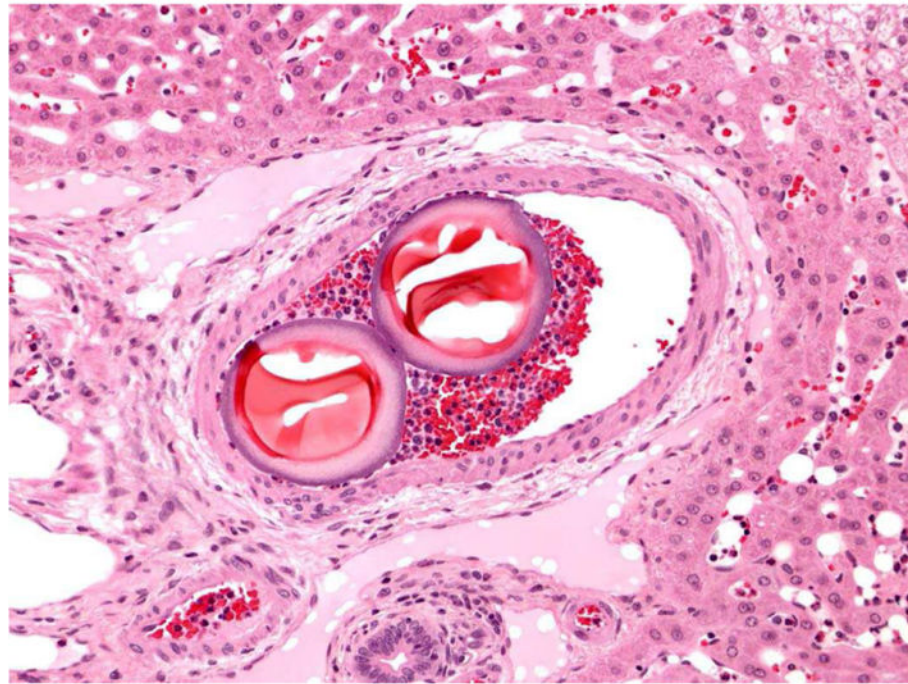
Figure 2. Tumor doxorubicin levels (ng/mg tissue) at various times after treatment in the three treatment groups.



A.



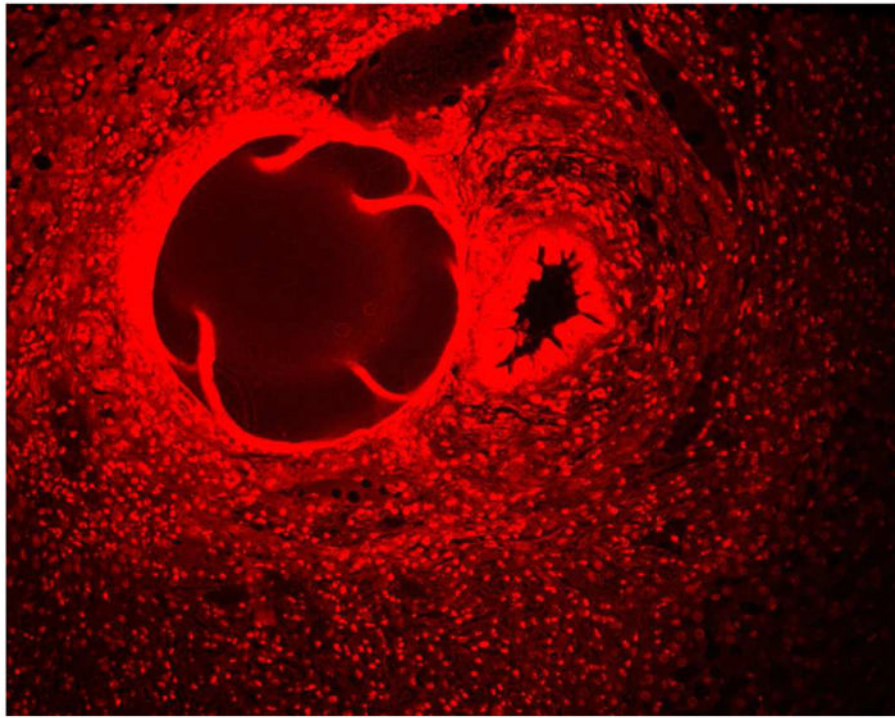
B.



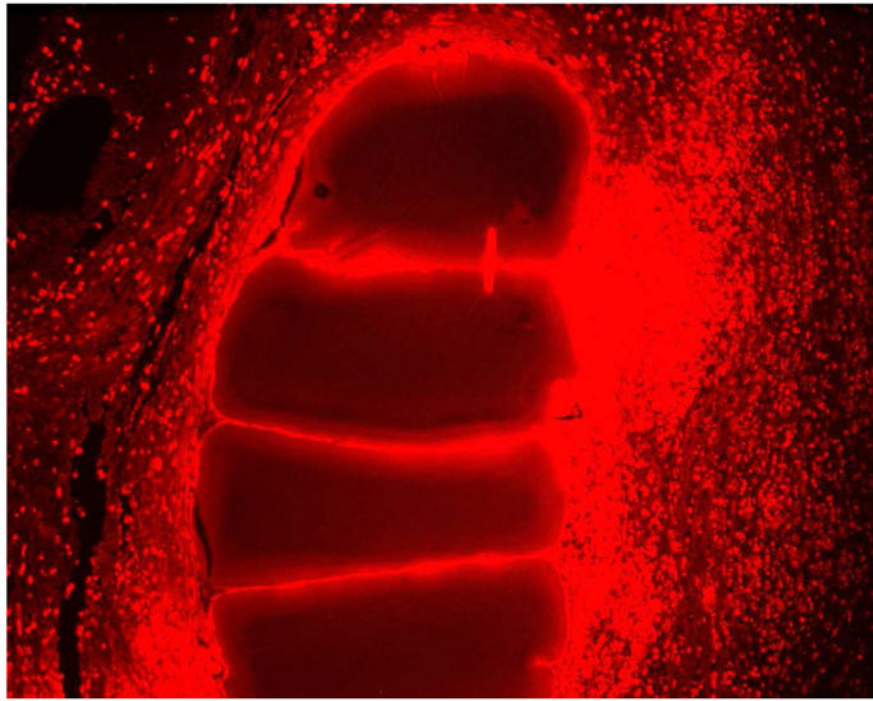
C.

Figure 3.

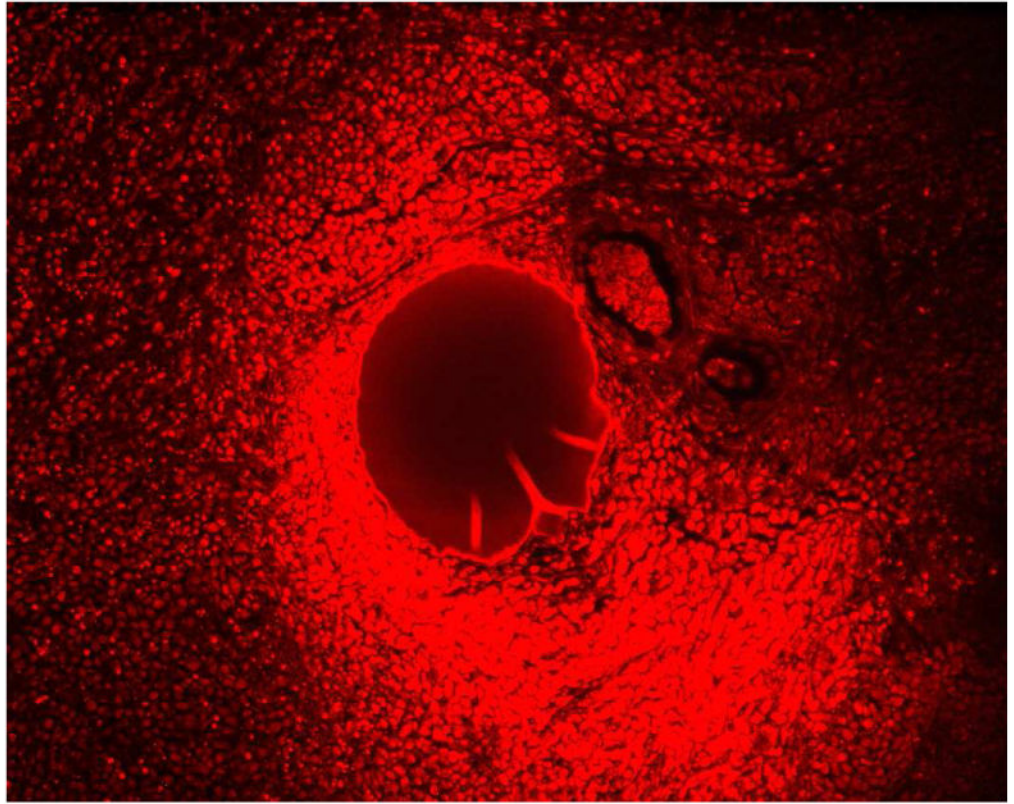
Photomicrographs (all hematoxylin and eosin [H&E] stain): **(A)** Multiple eosinophilic QuadraSpheres occluding a vessel (original magnification, $\times 50$). QuadraSpheres were deformed and conformed to the morphology of the vessel lumen and adjacent particles. **(B)** A basophilic QuadraSphere in a peritumoral vessel in the liver (original magnification, $\times 100$). **(C)** Two Embospheres in a vessel. These Embospheres are round, eosinophilic structures with basophilic rims (original magnification, $\times 200$).



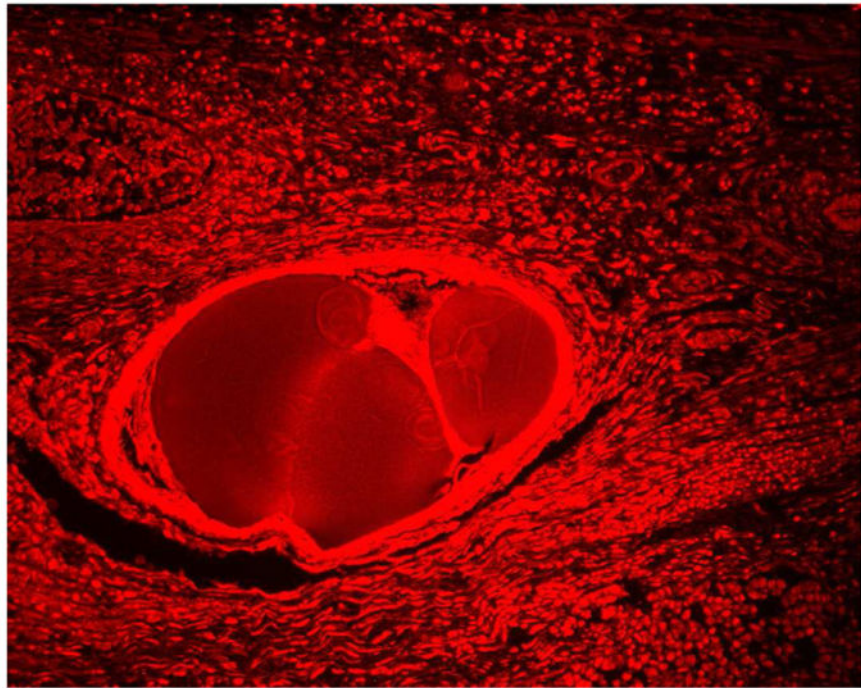
A



B



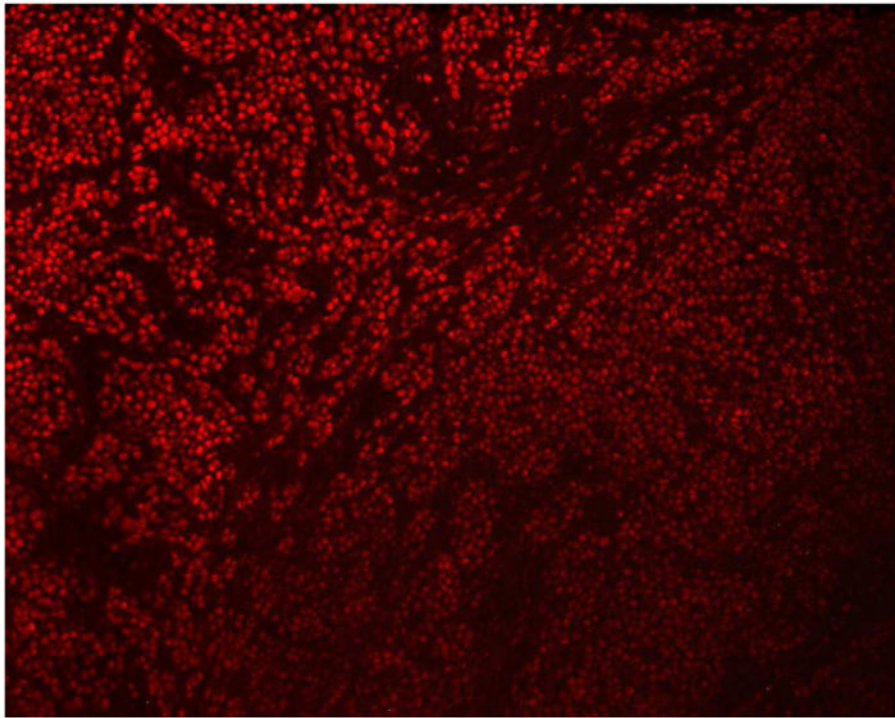
c



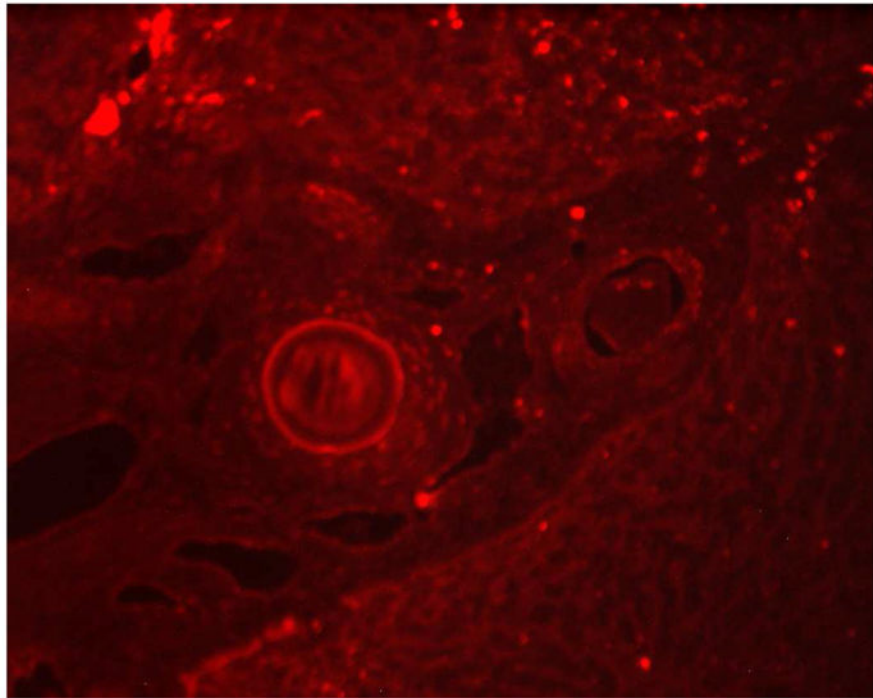
D

Figure 4.

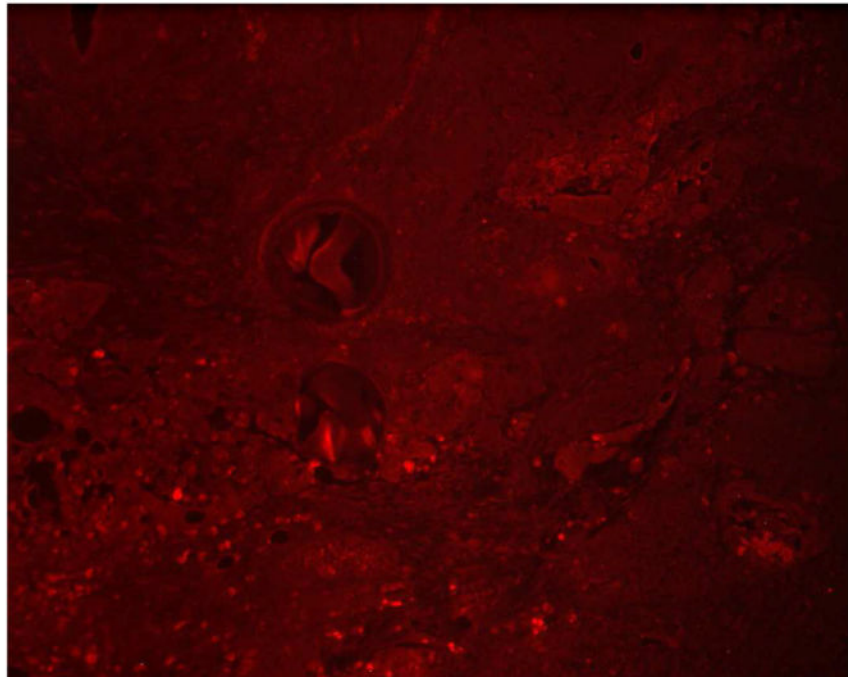
Doxorubicin fluorescence in the QuadraSphere group. Photomicrographs (original magnification, $\times 10$) in animals euthanized 1 (**A**), 3 (**B**), 7 (**C**), or 14 (**D**) days after treatment show fluorescence in and around the microspheres. The fluorescence intensity was similar at all times.



A



B



C

Figure 5.

Doxorubicin fluorescence in the transarterial chemoembolization (TACE) group. Photomicrographs (original magnification, $\times 10$): Intratumoral fluorescence in an animal killed 1 day (**A**) after treatment. Minimal or no intratumoral fluorescence is seen in animals killed at 3 days (**B**) or 7 days (**C**) after treatment. Note the Embospheres in (**B**) and (**C**).