4open 2022, **5**, 17

https://doi.org/10.1051/fopen/2022018

4 Open

Special issue - Inorganic Nanoparticle Luminophore: Design and Application.
Guest Editor: Prof. Prasun Mukherjee

Available online at:
www.4open-sciences.org

RESEARCH ARTICLE OPEN ACCESS

# Trifunctional fluorescent manganese ferrite nanoparticles for hyperthermia therapy, cell probing and drug delivery

Madhuri Mandal Goswami[1,*] and Debarati De[2]

[1] Centre for Biomedical Research, Bharat Sevashram Sangha Hospital, Diamond Harbour Road, Joka, Kolkata 700104, India
[2] CRNN, Calcutta University, Block-JD, Sector III-2, Salt Lake, Kolkata 700106, India

Received 4 July 2022, Accepted 14 September 2022

**Abstract –** Here we have reported a new protocol for drug delivery from hollow sphere manganese ferrite nanoparticles (HMF NPs). The crystalline structure of HMF NPs is obtained from XRD measurement and the morphological and elemental analysis are obtained from FESEM & TEM measurements. Here the HMF NPs are properly designed for delivery of dopamine (DA) as anticancer drug to cancer site. The DA polymerizes to a giant molecule polydopamine (PDA) inside hollow HMF in presence of TRIS buffer at pH (8.5) and a composite, HMF-PDA is formed. Being giant molecule polydopamine remain stable inside the hollow particles, but when these HMF-PDA come in contact of low pH i.e. pH 5 (cancer cells pH), free DA starts to be released. At hyperthermic temperature (45 °C) release enhances compare to physiological temperature (37 °C). The DA release studies are monitored by UV-visible absorption spectroscopy with progress of time at different temperatures and pH. It has been observed that HMF-PDA has fluorescent property whereas DA has no such effects. So, incorporation of PDA inside HMF and tagging of HMF-PDA with cancer cells can also be monitored by fluorescence imaging. Hence, we have successfully synthesized trifunctional HMF-PDA composite which can serve three purposes like cancer cell probing by fluorescence imaging, hyperthermia therapy and drug delivery by magnetic field and pH trigger method.

**Keywords:** Hollow manganese ferrite nanoparticles, Drug delivery, Dopamine, pH and temperature responsive

## Introduction

Cancer is one of the harmful diseases in the world. There are many types of cancer treatment such as surgery, radiation therapy, chemotherapy etc. which have several side effects. Besides of these treatments, nanoparticle-based drug delivery systems (DDS) grow interest among the researchers due to its more efficiency for cancer treatment [1]. Many anticancer drugs have been developed which often limits their clinical use due to their low selectivity, non specificity, poor aqueous solubility and low bioavailability. To overcome these problems researchers have synthesized nanoparticles and functionalized these NPs in such a way which helps a sustained and a controlled release of its cargo at cancer sites. Magnetic nanoparticle based anticancer DDS were used due to their property of enhanced permeation retention effect for which the magnetic nano particles (MNPs) are accumulated and retained in the cancerous extracellular matrix for longer time [2–4]. Many times, chemotherapy becomes non efficient due to the poor cellular internalization of drugs which limits the drug activity and dosages of anticancer drugs administered for treatment become lower than its therapeutic level [5, 6]. To overcome these problems, controlled release of drugs at cancer sites have been attempted. Recent years, pH responsive drug release were more frequently used due to difference of pH between different tissues inside the body. The pH of cancer tissue (pH 5.5) is less than the pH of normal tissue (pH 7.4). So, the cancer cells are more acidic compare to normal cells. Therefore, various pH responsive targeted drug deliveries by MNPs have been developed for better drug delivery [7–10].

Currently the anticancer drugs used are very toxic for normal cell line. We have chosen dopamine (DA) as anticancer drug which is nontoxic for normal cell line but toxic to cancer cell line. Dopamine (DA) is an organic chemical of catecholamine and phenylalanine families which plays an important role in the brain and body hence up to certain level it is not toxic what is already tested. Previous studies show that DA also acts as an anti-angiogenic drug in cancer treatment. An anti-angiogenic drug prevents the growth of new blood vessels which is generated by the process of angiogenesis. Earlier studies have shown that DA inhibits the action of vascular endothelial growth factor-A (VEGF-A) on blood vessels and blocks the growth of new blood vessels in tumour. According to Sarkar and other's report, DA enhances the efficacy of anti cancer drugs for

*Corresponding author: madhuri.snbose@gmail.com

the treatment of breast and colon cancer [11]. DA does not have several side effects compare to other anti-angiogenic drugs. Basu and his colleagues reported that DA did not affect the liver function, renal function etc like other popular cancer drug. On other hand, DA also prevent neutropenia (low neutrophil count) which is induced by many anti cancer drugs like 5-flurouracil [12]. Therefore, the delivery of DA by MNPs at cancer extracellular matrix will opens a new research gate in cancer treatment.

In this paper, we have reported the synthesis of hollow shaped manganese ferrite nanoparticles (HMF NPs) by solvothermal method. We have successfully developed pH responsive and temperature dependent polydopamine loaded HMF NPs (HMP-PDA NPs) which is capable to release DA at cancer cells due to its low pH. But slow release takes place in case of normal blood pH. HMF-PDA NPs have good capacity to release of DA at cancer regions. Due to the hollow shape, the polydopamine is not only attached on the outer surface, but also enters into the core of hollow and hence it takes more time to release DA. Because of the hollow shape and porosity of HMF NPs it become helpful for sustained release of DA. From our studies it was also shown that the release of DA from the HMF-PDA NPs was greater at hyperthermic temperature i.e. 45 °C than normal body temperature. So, our HMF NPs will serve as a very good drug carrier with different stimuli dependent drug release properties.

## Material and method

### Material

All the chemicals ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$), manganese chloride hexahydrate ($MnCl_2 \cdot 6H_2O$), ethylene glycol, ethanol, urea, oleyl amine, phosphate buffer solution (PBS) were purchased from Sigma Aldrich and Merck.

### Method of synthesis of material

The HMF NPs was synthesized by solvothermal method. Here, $FeCl_3$ and $MnCl_2$ (with a ratio of 2:1 by molar) were dissolved in 40 mL ethylene glycol and 20 mL ethanol by proper stirring and mixing. After that 10 g of urea and 2 mL of oleyl amine were added with this solution. Then the total solution was transferred to a Teflon lined stainless steel autoclave and heated at 200 °C temperature for 18 h. After that the sample was allowed to cool down until it goes to room temperature, then the sample was washed with alcohol for several time and then dried for different experiments and investigations.

### Loading of NPs with dopamine

To incorporate the dopamine inside the HMF NPs, 25 mg of HMF NPs was added with 2 mL of aqueous solution of dopamine hydrochloride at the concentration of 50 mg/2 mL and stirred at room temperature for 5 h. In this process dopamine is adsorbed on the surface of the HMF NPs and also enters into core of hollow. After that TRIS buffer (pH 8.5) was added to the solution of dopamine loaded HMF NPs and further stirred for 3 h to allow the polymerization of dopamine inside the core of HMF and finally polydopamine loaded hollow manganese ferrite NPs (HMF-PDA NPs) are formed. Then the sample was centrifuged and washed with distilled water gently to remove excess free dopamine. The sample was then allowed to dry and stored at 4 °C for further experiment.

### Structure, morphology and elemental characterization of HMF

The size and structure of the HMF NPs was characterized by XRD measurement. The particles size was analyzed from XRD pattern by using Scherer formula. The XRD of powder samples were recorded at room temperature by using Rigaku Miniflex II diffractometer using Cu $K_\alpha$ ($\lambda = 1.5418$ Å) radiation source in the incident angle $2\theta$.

The morphology and elemental composition of this NP was obtained by using field emission scanning electron microscopy (FESEM) and EDAX spectra. For FESEM analysis, the sample was drop casted on silicon wafer. Small amount of sample was dissolved in alcohol and probe sonicated for proper dispersion. Then the solution was drop casted on silicon wafer and dried in vacuum desiccator. Gold coating is done before FESEM measurement. The finer morphology of this NP was obtained by TEM analysis. The TEM analysis was performed in TECHNAI $G^2$ TF20 at 200 kV. For TEM analysis, the prepared sample (samples prepared for FESEM) was drop casted on 300-mesh carbon-coated copper (Cu) grid and dried it in vacuum desiccator. To verify any change in size after conjugation of PDA with HMF the DLS study was made on HMF-PDA particles by dispersing them in aqueous medium. To confirm the conjugation of PDA with HMF, FTIR study was also performed.

### Dopamine release studies

To study the release of dopamine from polydopamine loaded HMF-PDA NPs, 1 mg of the particles was dispersed in 2 mL of phosphate buffer solution (PBS). The release of DA from polydopamine loaded HMF NPs for two pH at 7.4 and 5 at normal body temperature (37 °C) and hyperthermia temperature (45 °C) are studied by monitoring UV-Vis spectroscopy with time. The HMF-PDA particles were kept under AC magnetic field inside a solenoid for higher temperature (45 °C) drug release measurement. To do the drug release study on MDAMB-231 cell line, the cells were incubated in $CO_2$ incubator by treating them with HMF-PDA (1 mg/2 mL) for different time interval at 45 °C and pH 5 following the proper protocol of cell culture. Cell images were acquired at different interval by phase contrast microscope (Olympus-CKX-53, Japan).

### AC magnetic field induced heating

To measure the heat induced on the HMF NPs under AC magnetic field, we have prepared a basic solenoid with

174 no of turns operating at 230 volt with 50 Hz AC supply. For this study 1 mg of sample was dispersed in 2 mL of PBS solution and kept in 2 mL plate. This plate was kept under AC magnetic field of 7.897 mT inside the solenoid and then temperature was measured in a fixed time interval with a digital thermometer.

### Experiment on fluorescence imaging of HMF, HMF-PDA and after treatment of HMF-PDA with cancer cell line

At first, 1 mg of HMF-PDA was dispersed in 0.1 M $NaHCO_3$ solution and then sonicated for proper mixing. After that, the sample was allowed to continuous stirring at room temperature for 24 h in the dark. Then the particles were centrifuged at 10,000 rpm and washed with water gently and again dispersed in PBS solution. Then the PBS dispersed sample was incubated with MDAMB-231 cells for 3 h following proper protocol. Then fluorescence images were taken for all the HMF, HMF-PDA and the cancer cells after treating them with HMF-PDA by using fluorescence microscope (EVOS FL).

## Result and discussion

### Crystalline structure and morphology

XRD pattern of HMF NPs is shown in Figure 1. All the diffraction peaks are indexed and compared with JCPDS data (card no. 10-0319) which perfectly matches with the manganese ferrite spinel structure face-centered cubic lattice. The sharp diffraction peaks indicate high crystallinity. The crystalline size ($d$) of the HMF NPs was calculated by Debye Scherrer equation ($d = 0.9\lambda/(\beta\cos\theta)$) which was about 25 ± 2.5 nm.

The FESEM image of HMF NPs are shown in Figure 2a. From Figure 2a, it is observed that the particles are hollow in nature. Average diameter of the hollow sphere is around 150 ± 2.4 nm. The EDAX analysis was done on this sample and spectrum is shown in Figure 2b where elemental analysis is given in inset of Figure 2b. From which we can see all the elements Fe, Mn and O are present in Mn–ferrite particles. Si and Au are coming from Si-substrate and gold coating on sample. C is coming due to use of organic stabilizer during synthesis of particles.

Finer morphology and hollow nature of HMF NPs were confirmed from the TEM micrograph as shown in Figure 3a and it was seen that the size of shell thickness of HMF NPs was about 30 nm with particle size 150 nm with standard deviation ± 3. We can see here the particles are porous in nature. This porous nature will help in drug incorporation as well as drug release.

DLS study was done after conjugation of PDA with HMF and the image is shown in Figure 3b, which indicates increase in size to about 340 nm. It is due to surface functionalization of HMF by PDA. Hence a composite like structure of "HMF-PDA" is formed here.

FTIR study was performed to support the conjugation of PDA with HMF NPs. FTIR spectra for free HMF and after

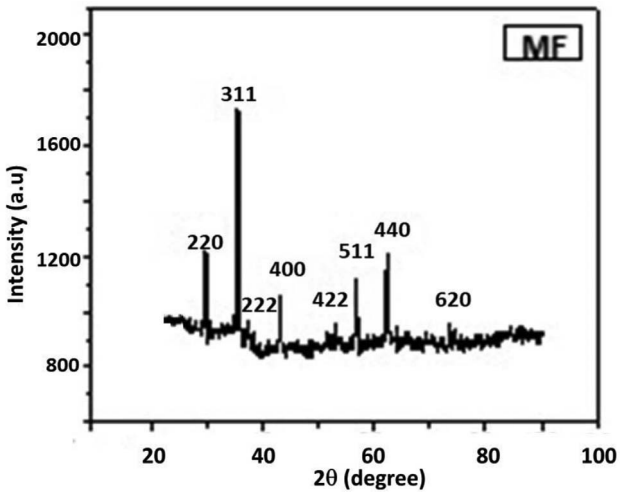


**Fig. 1.** XRD spectrum of HMF NPs.

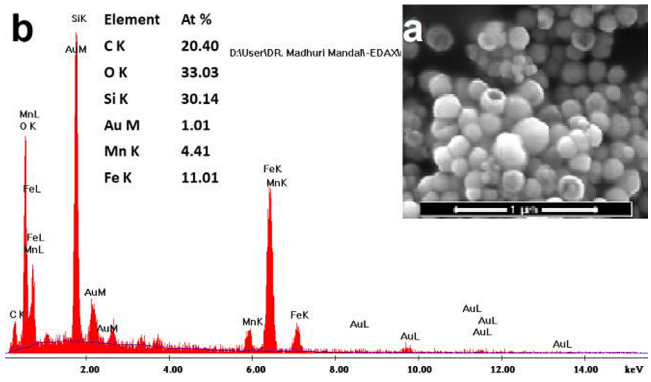


**Fig. 2.** (a) FESEM image of HMF NPs and (b) EDAX spectra with elemental analysis (inset) during FESEM measurement.

PDA loading in HMF are shown in Figure 3c. Here we see few peaks in the range of 3400 $cm^{-1}$ to 3600 $cm^{-1}$ are assigned to stretching vibrations of the O–H, C–N and N–H functional groups present in dopamine. One small peak is observed in 2170 $cm^{-1}$, corresponding to CH stretching vibration. Two peaks around 1650 and 1500 are assigned to aromatic C=C and C–N bonds present in the PDA, confirming the presence of aromatic benzene ring and amine groups in the PDA. The peak at 1450 $cm^{-1}$ and 900 $cm^{-1}$, corresponding to the bending vibration of CH and the aryl oxygen stretching vibration. Similar results are obtained in our previous studies also [13]. The peak in the low range at 600–450 $cm^{-1}$ is due to Fe–O and Mn–O bond which are coming from HMF. From these results it is evident that DA successfully bind with HMF. From fluorescence image we will see DA will bind with HMF by polymerization of DA, which we will discuss later in this paper.

### Dopamine loading and release studies

The amounts of DA release from HMF-PDA NPs were investigated from the absorbance values obtained from UV-Vis absorption spectra. The details release studies of

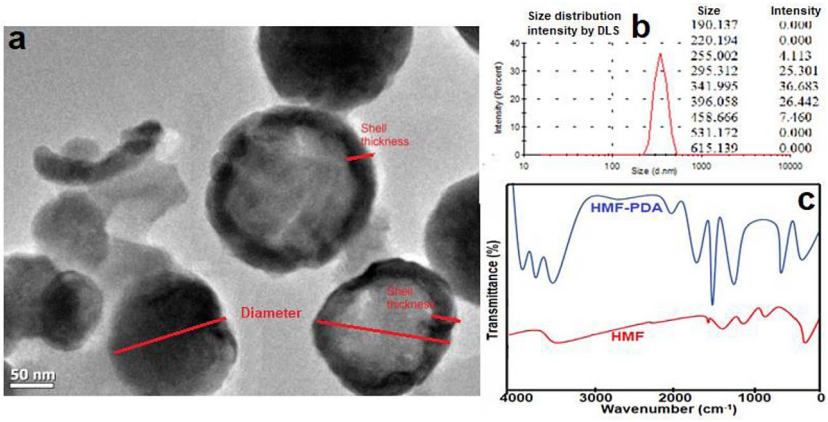


**Fig. 3.** (a) TEM results of HMF NPs, (b) DLS size distribution of HMF-PDA NPs, (c) FTIR spectra for bare HMF (red) and HMF-PDA (blue).

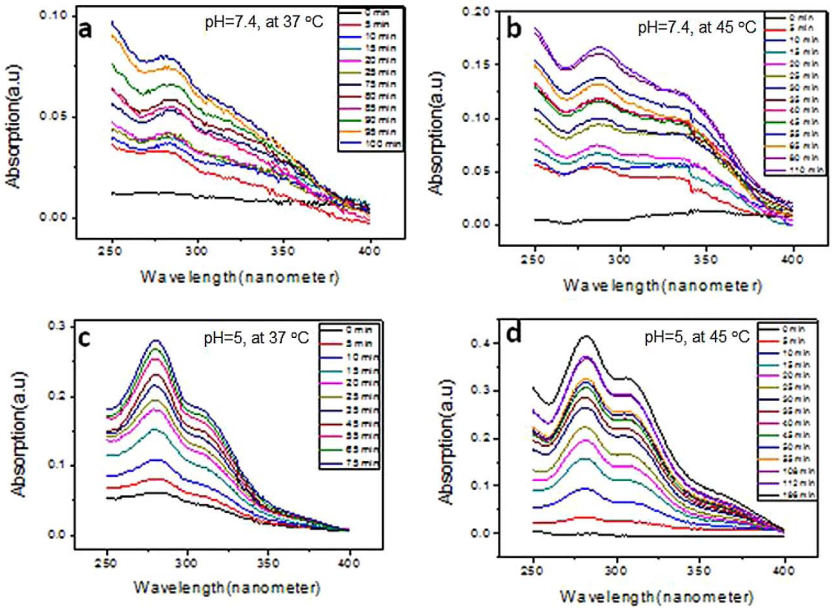


**Fig. 4.** Release of dopamine from polydopamine loaded HMF-PDA NPs. (a) in pH 7.4 at 37 °C, (b) in pH 7.4 at 45 °C, (c) in pH 5 at 37 °C and (d) in pH 5 at 45 °C.

DA from HMF-PDA NPs are shown in Figure 4 by UV-Vis spectroscopy. In these spectra we see an intense peak at 280 nm which is characteristic peak of DA which indicates release of DA from HMF-PDA. The drug release experiments were performed at two different pH and temperatures. Figures 4a and 4b show the UV-Vis spectroscopy for DA drug release from HMF-PDA NPs in pH 7.4 at temperature 37 °C and 45 °C, respectively. At 45 °C in pH 7.4 the release of DA from HMF-PDA NPs (Fig. 4b) was greater than release rate at 37 °C (Fig. 4a). On other side, the DA release at pH 5 at two different temperatures are shown in Figures 4c and 4d. By comparing all the DA drug release data, the highest release of DA from HMF-PDA NPs was observed at 45 °C at pH 5 (Fig. 4d). In our previous papers we have observed similar results [13–15].

Here to incorporate DA, a sufficient amount of time (5 h) was allowed for DA to go inside the hollow HMF NPs, then it was stirred in presence of TRIS buffer with pH 8.5 to polymerize DA to PDA. Because of giant structure of PDA, it cannot come outside easily from the hollow particles and remain stable inside the particles. But at lower pH and higher temperature the PDA break down to DA which are comparatively much smaller than PDA and can come out easily from porous hollow particles. From Figure 4 it is clearly shown that the HMF-PDA NPs has an efficiency to release DA which indicates the successful incorporation of DA inside HMF NPs and formation of PDA inside it and for this reason DA may be slowly released from the HMF-PDA NPs. It is well known that the pH of cancer cells is about 5 which is less than our normal cell pH i.e. pH 7.4. The optimum pH for producing of polydopamine from dopamine was pH 8.5. When the polydopamine loaded NPs were kept in pH 5 solution, then the DA are formed from polymer of DA (PDA) and degraded free DA was released from

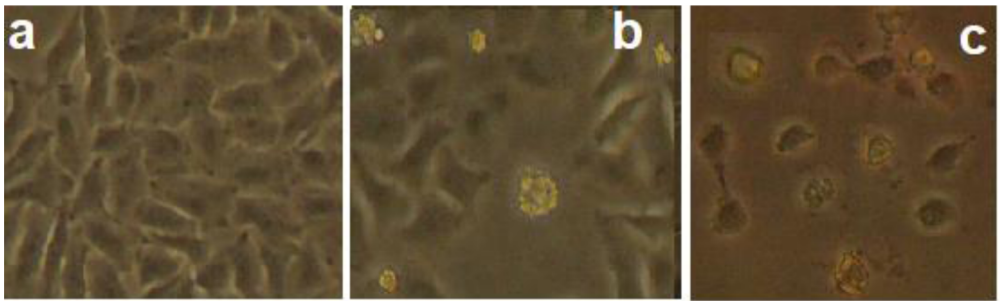


**Fig. 5.** Images of MDAMB-231 cells after drug delivery at different time interval (a) at 0 time, (b) after 30 min and (c) after 60 min.

HMF-PDA, but at pH 7.4, the releasing efficacy of DA is less compared to pH 5 as degradation rate of DA from PDA is lower at higher pH. So, in cancer cells the dopamine release will be better than in normal cell which is a very advantageous for selective drug release on cancer cell lines and will give a better treatment protocol for cancer therapy.

Previous research reports indicate that the polydopamine NPs did not interrupt the viability or proliferation of many kinds of normal cells even at very high doses [16, 17]. Therefore, polydopamine acts as a good drug carrier due to its good biocompatibility, greater circulating time inside the body fluid. After DA release the remaining polydopamine loaded NPs must be released from body. There is certain evidence about the degradation of polydopamine nanoparticles. Langer's group have demonstrated after their in-vivo studies that the polydopamine were fully degraded after 8 weeks [18]. Another possible pathway for bio degradation of polydopamine is the oxidation-induced degradation process. In the human body, multi-subunit enzymes nicotinamide adenine dinucleotide phosphate oxidase (NADPH oxidase) is generated which helps to degrade the polydopamine [19]. But here another question still remains unsolved that is degradation of HMF NPs. Our next trial will be to investigate on that. It is an in-vivo study, for which we need some permission. Therefore, at present we can't do this experiment.

Drug release study was performed on cancer cell lines MDAMB-231 at pH 5, 45 °C temperature keeping the cells at incubator and at three different times, initially without drug release and after 30 and 60 min of drug release, images were taken for the cells, which are shown in Figures 5a–5c. From this figure it is evident that initially all the cells are live whereas after 30 min of drug release few of the cells are dead and after 60 min of drug release almost all the cells become dead. From this we can say that this method will be very efficient for cancer cell death at a reasonably short time.

## Temperature gain measurements for the HMF NPs in the solenoid

Table 1 shows the temperature gained by the particle in the PBS solution inside the solenoid (with applied AC magnetic field), for particular time intervals. We can see the particle solution gain heat slowly with time. AC magnetic field is agitating the unit magnet of NPs due to magnetic property of these particles. Under AC magnetic field, as they start to fluctuate heat generation starts due to dynamic hysteresis loss and Neel relaxation which is the main condition for magnetic hyperthermia. From this temperature rise we calculated the specific absorption rate (SAR) using the following equation [20],

$$M_d \cdot (C_p/M_{np}) \cdot (\mathrm{d}T/\mathrm{d}t)_{t=0},$$

where $M_d$ is mass of dispersion medium, $M_{np}$ is mass of nanoparticles dispersed, $(\mathrm{d}T/\mathrm{d}t)_{t=0}$ is the slope at initial in terms of time interval (second) and temperature interval (K). $C_p$ is the heat capacity of medium. Here we consider it 4.184 J/g/K which is $C_p$ for water medium. We find out SAR value for our HMF sample is 62.76 W/g. SAR value depends on many parameters such as, size, magnetic properties, applied AC field, frequency and quantity of NPs dispersed in solution.

**Table 1.** Temperature gain by HMF under AC magnetic field.

| Time (min) | Temperature of HMF dispersion under AC magnetic field (°C) |
|---|---|
| 0 | 25 |
| 1 | 25.45 |
| 2 | 25.95 |
| 3 | 26.43 |
| 4 | 26.92 |
| 6 | 27.97 |
| 8 | 28.98 |
| 10 | 30.01 |
| 12 | 30.98 |
| 14 | 32.01 |
| 16 | 33.00 |

## Photoluminescent properties of HMF and HMF-PDA

We have investigated the fluorescence properties of HMF and HMF-PDA NPs under the fluorescence microscope, which are shown in Figures 6a and 6b, respectively. Here we see the free HMF does not show any fluorescent colour, where-as HMF-PDA show deep red fluorescent image. From this experiment we can assume that it will be a facilitating property of HMF-PDA to investigate whether these materials are attached with cells or not. To investigate

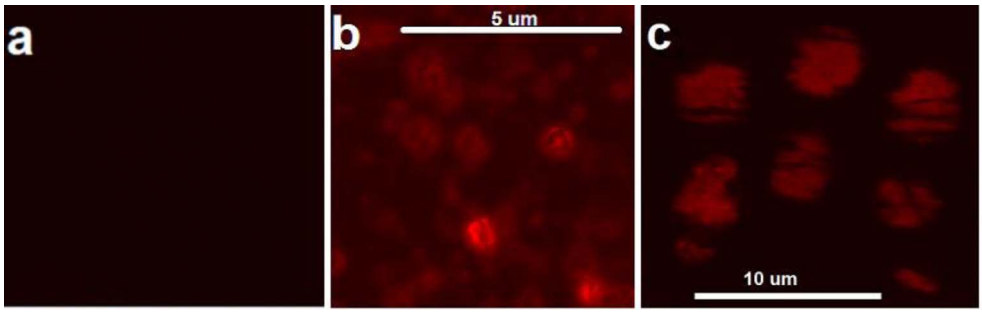


**Fig. 6.** Fluorescence images of (a) free HMF, (b) HMF-PDA and (c) HMF-PDA up-taken MDAMB-231 cells.

this, we incubated the HMF-PDA particles with cancer cell line MDAMB-231 following the proper protocol and took the fluorescence image which is shown in Figure 6c. This shows a red colour image of the cells. From this image it is clear that particles are up-taken by cancer cells and can be tracked the tagging of the particles with cells and up-taken of the particles by the cells can also be monitored by this red colour fluorescence image. After confirming the up-taking of particles by the cells, the hyperthermia therapy will be wise to perform. More the up-taking more will be efficiency for hyperthermia therapy as more heat will be generated.

## Conclusion

We have prepared the hollow manganese ferrite nanoparticles with suitable porosity which is very much useful for selective DA drug release at lower pH and higher temperatures. From XRD data it was shown that the particles are pure phase spinel like manganese ferrite and the morphological structure confirmed about their hollow shape. The effective release of DA is greater in pH 5 at 45 °C by HMF-PDA NPs. So, the pH and temperature responsive polydopamine loaded HMF NPs would be a promising drug delivery agent as a DA drug carrier for cancer treatment. The release of drug changes with temperature and pH, so we can achieve a controlled drug release by applying the AC magnetic field from outside the body with change of applied field and frequency. This study offers a new area of dopamine delivery at cancer site by a new method.

## Acknowledgments

Authors are thankful to the Department of Science and Technology, Government of India for the funding under the project DST/WOS-A/CS-36/2020. D. De is grateful to Department of Science and Technology, Government of India for Inspire fellowship.

## Conflict of interest

Dr. Madhuri Mandal Goswami declare that she has no conflict of interest. Ms Debarati De also declare that she has no conflict of interest.

## References

1. Du JZ, Du XJ, Mao CQ, Wang J (2011), Tailor-made dual pH-sensitive polymer-doxorubicin nanoparticles for efficient anticancer drug delivery. J Am Chem Soc 133, 44, 17560–17563.
2. Farokhzad OC, Langer R (2009), Impact of nanotechnology on drug delivery. ACS Nano 3, 1, 16–20.
3. Peer D, Karp JM, Hong S, Farokhzad OC, Margalit R, Langer R (2007), Nanocarriers as an emerging platform for cancer therapy. Nat Nanotechnol 2, 12, 751–760.
4. Torchilin VP (2007), Micellar nanocarriers: Pharmaceutical perspectives. Pharm Res 24, 1, 1–16.
5. Ulbrich K, Subr V (2004), Polymeric anticancer drugs with pH-controlled activation. Adv Drug Deliv Rev 56, 7, 1023–1050.
6. Etrych T, Jelinkova M, Rihova B, Ulbrich KJ (2001), New HPMA copolymers containing doxorubicin bound via pH-sensitive linkage: Synthesis and preliminary in vitro and in vivo biological properties. J Control Release 73, 1, 89–102.
7. Karimi Z, Abbasi S, Shokrollahi H, Yousefi Gh, Fahham M, Karimi L, Firuzi O (2017), Pegylated and amphiphilic Chitosan coated manganese ferrite nanoparticles for pH-sensitive delivery of methotrexate: Synthesis and characterization, Mater Sci Eng C 71, 504–511.
8. Babul Reddy A, Manjula B, Jayaramudu T, Sadiku ER, Anand Babu P, Periyar Selvam S (2016), 5-fluorouracil loaded chitosan–PVA/$Na^{+}$MMT nanocomposite films for drug release and antimicrobial activity. Nano-Micro Lett 8, 3, 260–269.
9. Majewski AP, Schallon A, Jerome V, Freitag R, Muller AHE, Schmalz H (2012), Dual responsive magnetic core–shell nanoparticles for nonviral gene delivery and cell separation. Biomacromolecules 13, 857.
10. Chan N, Laprise-Pelletier M, Chevallier P, Bianchi A, Fortin MA, Oh JKJ (2014), Multidentate block–copolymer–stabilized ultrasmall superparamagnetic iron oxide nanoparticles with enhanced colloidal stability for magnetic resonance imaging. Biomacromolecules 15, 2146–2156.
11. Sarkar C, Chakroborty D, Chowdhury UR, Dasgupta PS, Basu S (2008), Dopamine increases the efficacy of anticancer drugs in breast and colon cancer preclinical models. Clin Cancer Res 14, 8, 2502–2510.
12. Sarkar C, Chakroborty D, Dasgupta PS, Basu S (2015), Dopamine is a safe antiangiogenic drug which can also prevent 5-fluorouracil induced neutropenia. Int J Cancer 137, 3, 744–749.
13. De D, Upadhyay P, Das A, Ghosh A, Adhikary A, Goswami MM (2021), Studies on cancer cell death through delivery of dopamine as anti-cancer drug by a newly functionalized cobalt ferrite nano-carrier. Colloids Surf A Physicochem Eng Asp 627, 127202–127208.

14. Dey C, Ghosh A, Ahir M, Ghosh A, Goswami MM (2018), Improvement of anticancer drug release by cobalt ferrite magnetic nanoparticles through combined pH and temperature responsive technique. ChemPhysChem. Wiley, 19, 2872.
15. Goswami MM (2016), Synthesis of micelles guided magnetite ($Fe_3O_4$) hollow spheres and their application for AC magnetic field responsive drug release. Sci Rep 6, 35721.
16. Ku SH, Ryu J, Hong SK, Lee H, Park CB (2010), General functionalization route for cell adhesion on non-wetting surfaces. Biomaterials 31, 9, 2535–2541.
17. Liu YL, Ai KL, Liu JH, Deng M, He YY, Lu LH (2013), Dopamine-melanin colloidal nanospheres: An efficient near-infrared photothermal therapeutic agent for in vivo cancer therapy. Adv Mater 25, 9, 1353–1359.
18. Bettinger CJ, Bruggeman JP, Misra A, Borenstein JT, Langer R (2009), Biocompatibility of biodegradable semiconducting melanin films for nerve tissue engineering. Biomaterials 30, 17, 3050–3057.
19. Cave AC, Brewer AC, Narayanapanicker A, Ray R, Grieve DJ, Walker S, Shah AM (2006), NADPH oxidases in cardiovascular health and disease. Antioxid Redox Signal 8, 5–6, 691–728.
20. Wang SY, Huang S, Borca-Tasciuc DA (2013), Potential sources of errors in measuring and evaluating the specific loss power of magnetic nanoparticles in an alternating magnetic field. IEEE Trans Magn 49, 1, 255–262.

**Cite this article as:** Mandal Goswami M & De D, 2022. Trifunctional fluorescent manganese ferrite nanoparticles for hyperthermia therapy, cell probing and drug delivery. 4open, **5**, 17.