**Magnetocaloric Materials for Room Temperature, Magnetic Refrigeration & Biomedical Applications - A Review**

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**Abstract**

Over the past two decades, there has been an exponential surge in research focused on studying and developing magnetocaloric materials, largely motivated by their application in energy-efficient and environmentally friendly magnetic refrigeration technologies. The magnetocaloric effect (MCE), which refers to the temperature change of a magnetic material upon the application or removal of a magnetic field, has emerged as a revolutionary cooling mechanism that offers notable advantages over conventional gas compression refrigeration. Specifically, cooling systems that operate on MCE principles can attain higher efficiencies, reduced greenhouse gas emissions, and diminished reliance on ozone-depleting refrigerants. The potential of MCE-based refrigeration has led to an intense focus on identifying advanced magnetocaloric materials and optimizing their properties. In sync with these developments, the unique thermal characteristics displayed by magnetocaloric materials have also shown considerable promise for precise biomedical applications such as targeted drug delivery, hyperthermia cancer treatment, and medical imaging. Research on evaluating the biocompatibility of these materials and demonstrating their safety and effectiveness is still in the early stages. Overall, the multifaceted applications of magnetocaloric materials in both refrigeration technologies and biomedicine have positioned MCE as an exciting field that warrants a deeper examination of the opportunities and challenges that define this space. This review paper seeks to provide a comprehensive look at recent results and future trends associated with developing magnetocaloric materials and leveraging their magnetothermal responses for magnetic heat pumps/refrigerators as well as disruptive biomedical diagnoses and therapies that assure maximum therapeutic impact

**Key Words**

Magnetocaloric effect, Magnetic Refrigeration, Hyperthermia, Magnetic drug delivery.

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**1. Introduction**

The magnetic refrigeration phenomena known as the Magnetocaloric Effect (MCE) was first identified earlier than 1917 by physicists Weiss and Piccard of France and Switzerland [1]. This effect causes specific materials to heat up when exposed to a magnetic field, and materials displaying this property are known as magnetocaloric materials. Harnessing the MCE allows for the implementation of a magnetic cooling cycle close to room temperature. FeRh alloys, discovered 26 years ago by Nikitin [1][2], have demonstrated the highest measured MCE value to date. A pivotal advancement in magnetocaloric research was the identification of the giant MCE, as documented by Pecharsky and Gschneidner [2]. The diverse range of practical applications has drawn significant interest from researchers and industrialists to the field of MCE. The recent surge in MCE investigations can be attributed to advancements in developing new magnetocaloric materials over the past two decades. Despite more than a century of study, widespread practical applications of the MCE remain challenging. Issues such as the high cost of magnetic field sources, underdeveloped manufacturing technologies for MCE materials, constraints in suitable shapes for refrigerator use, and limitations in significantly extending the working cycle frequency need to be addressed. The International Institute of Refrigeration (IIF/IIR) has undertaken numerous promising initiatives in magnetic refrigeration, fostering optimism for the future of this technology. However, the initial high entry costs into refrigeration markets present a hurdle, despite the considerable potential of MCE-based equipment. Integration of magnetocaloric materials into heat pipes lays the groundwork for this technology, facilitating the creation of cooling systems without harmful reagents.

In the past, conventional gas compression (CGC) technology was commonly employed in cooling applications. CGC operates by expanding and compressing gases within refrigerators. However, this method releases harmful chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), which contribute to ozone layer depletion. To mitigate this environmental impact, an eco-friendly cooling technology known as the magnetocaloric effect (MCE) has been recently introduced. Compared to CGC, MCE significantly reduces the emission of CFCs and HFCs, thus minimizing ozone layer damage and safeguarding environmental well-being. Additionally, MCE demonstrates superior cooling efficiency, offering a 20-50% improvement over CGC. Given its numerous advantages over CGC, MCE has emerged as a viable alternative cooling solution. In essence, MCE involves the reversible temperature change observed when altering the magnetization of a ferromagnetic or paramagnetic material.

In essence, the characteristics of the Magnetocaloric Effect (MCE) for any given material under constant pressure are reliant on both the absolute temperature and the variation in magnetic field (∆H = Hf - Hi), where Hf and Hi denote the final and initial magnetic fields experienced by the material, respectively. This phenomenon can also be defined as the isothermal alteration of entropy (∆S) and the adiabatic modification of temperature (∆T) resulting from changes in the magnetic field H. The value of ∆T can be directly measured using a thermometer or indirectly inferred from specific heat data, while ∆S is derived from the material's magnetization or specific heat. Typically, the following equation represents the change in entropy: [1]

ΔS = ∫ .dH

The Magnetocaloric Effect (MCE) offers superior cooling capabilities and environmental benefits, along with a wide range of applications. This article primarily emphasizes recent advancements in room-temperature (RT) MCE materials and their practical uses.

Furthermore, the Magnetocaloric Effect (MCE) holds significant potential in biomedical applications, particularly in hyperthermia treatment and drug delivery [3]. Ongoing research aims to enhance drug delivery to tumors with minimal side effects compared to conventional methods, with a focus on achieving swift diagnosis and precise treatment. Magnetic drug delivery involves directing drugs to targeted tissues using an external magnetic field, potentially addressing issues associated with traditional delivery systems such as lack of target specificity. A notable drawback of conventional drug delivery is the accumulation of anti-cancer medications in tumor cells through permeability and retention effects, often resulting in adverse effects on healthy tissues due to leaky blood vessels. Magnetic drug delivery systems offer a solution to this problem by precisely guiding drugs to tumors using an external magnetic field, thereby sparing healthy tissues. Furthermore, magnetic drug delivery systems show promise in treating various conditions, including gene therapy, hearing loss, nervous system disorders, and tumors. This article focuses on MCE materials' applications in biomedicine and alloys and oxides that are suited for usage close to room temperature.

**2. Fundamental Aspects**

Present research on the Magnetocaloric Effect (MCE) split into two primary categories. The first approach involves characterizing new materials, with a focus on investigating their traditional characteristics of magneto-thermal properties. This method allows for observing a wide temperature range. One effective strategy is to utilize a series of materials with varying levels of magnetic components, which contribute to the MCE. However, it's essential to recognize that magnetic entropy change alone cannot accurately assess the performance of MCE in real-world applications. This is because magnetic entropy is an indirect and immeasurable parameter that only offers approximate estimation of an MCE value. In such cases, it's advisable to measure the adiabatic temperature change to directly gauge the material's behavior under consideration.

Another avenue in the exploration of Magnetocaloric (MC) materials entails examining subtle effects that significantly impact understanding the physics of the phenomena. These discoveries could subsequently have a profound influence on practical applications in the near future. An example of this approach involves studying conventional materials but with increased chemical purity and enhanced crystal structures. This method seeks to delve deeper into the complexities of material properties to improve comprehension and potentially uncover new applications.

**3. Principle and working of magnetic refrigeration**

Magnetic refrigeration relies primarily on a fundamental thermodynamic property of magnetic materials called the Magnetocaloric Effect (MCE). This effect induces a temperature change when the material is exposed to a magnetic field under adiabatic conditions. When subjected to a magnetic field, the temperature increases, and it decreases upon removal, showcasing a reversible and nearly instantaneous effect. The MCE offers several advantages over CGC technology. Magnetic cooling achieved through MCE addresses two key challenges associated with CGC systems:

i. Environmental challenge: MCE provides a gas-free solution, mitigating environmental concerns linked with traditional gas compression systems.

ii. Economic challenge: MCE aids in reducing energy consumption and improving efficiency, thus tackling economic concerns related to energy usage in refrigeration systems.

Cooltech, a globally renowned magnetic refrigeration firm based in Paris and Strasbourg, France, has unveiled the inaugural commercial magnetic cooling system as a component of its Magnetic Refrigeration System (MRS) series. The MRS 400 boasts an impressive 400 watts of cooling capacity, sustaining internal temperatures within the range of 35.6°F to 41°F (2°C to 10°C), ensuring optimal conditions for safe food preservation. In contrast to conventional refrigeration systems reliant on refrigerant gases, Cooltech's magnetic cooling system employs a glycol-water coolant, offering an environmentally friendly solution with minimal energy consumption and mitigating its impact on climate change..

Operating at low pressure and characterized by virtually vibration-free rotational speed, the magnetic unit maintains noise levels below 35 decibels, leading to decreased maintenance expenses. Furthermore, the entire system offers a nearly indefinite lifespan, guaranteeing long-lasting reliability and sustainability.

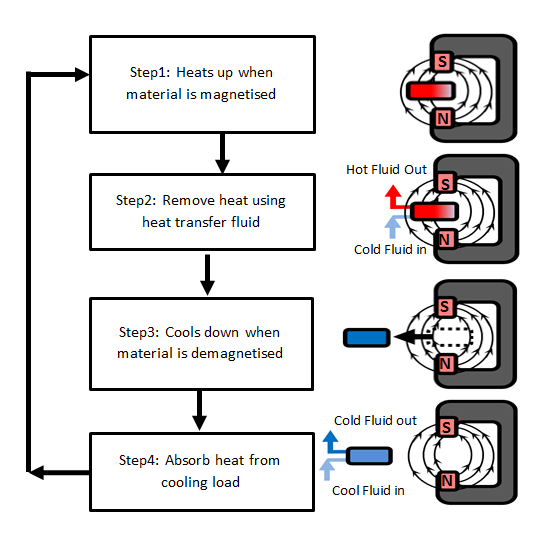
With cooling capacities spanning from 200 watts to 700 watts, the MRS series is tailored for diverse commercial refrigeration purposes, encompassing medical refrigerators, display cabinets, beverage dispensers, storage units, and wine cellars. This market sector, valued at over $20 billion annually, underscores the versatility and profound potential impact of Cooltech's magnetic refrigeration technology.

Figure1: Schematic showing basic working principle of magnetic refrigeration

Credit: Sirach’s Metkel yebiyo Cooltech applications

In a Magnetic refrigeration system, magnetocaloric alloys experience a sequence of magnetization-demagnetization cycles under controlled magnetic fields. Each cycle generates a temperature gradient in the material, and the rapid repetition of these cycles eventually sets the final and stable hot and cold temperatures within the refrigeration system.

**4. Magnetocaloric materials for room temperature applications**

This section delves into a detailed exploration of magnetocaloric materials suitable for room temperature applications, as outlined in Table 1. Among these materials, Gadolinium (Gd) emerges as a prominent choice for commercial applications at room temperature, given its transition temperature closely matching room temperature (294K) [2]. Gd displays notable isothermal entropy changes and adiabatic temperature changes, measuring 10 J/kg-K and 11K, respectively, with a magnetic field change of 5T. Despite efforts to alloy Gd with various other rare earth metals such as Tb, Dy, Er, and Tm, researchers have observed limited enhancements in MCE values and transition temperatures. Nevertheless, Gd retains significance for its transition occurring at room temperature and favorable MCE parameters compared to other rare earth metals.

**Table 1: Magnetocaloric effect of rare earth metals at room temperature**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **S.No** | **Sample/Composition** | **Tc (K)** | **∆Smax(J/Kg-K)** | **Ref** |
| 1 | Gd | 292 | 11.1 at 6 T | [4] |
| 2 | Tb | 230 | 20 at 7.5 T | [5] |
| 3 | Dy | 180 | 14.2 at 6.02 T | [6] |
| 4 | Ho | 134 | 1.8 at 6.02 T | [7] |
| 5 | Er | 85 | 1.2 at 6.02 T | [7] |
| 6 | Tm | 56 | - | [8] |

Table 2 presents a comprehensive overview of the magnetocaloric properties exhibited by various alloys suitable for room-temperature applications, serving as a valuable complement to the earlier discussion on magnetocaloric rare-earth metals. Notably, Gd90Ga10 emerges as a standout candidate, showcasing a maximum magnetic entropy change (∆SM) of 7.6 J/kg-K at a 5T magnetic field, as documented by Susilo et al. [9]. In another study by Liu et al. [10], it was observed that the addition of 5% or more Fe to Gd50Co45 alloy led to a reduction in its isothermal entropy change from 4.6 J/kg-K to 3.8 J/kg-K, while simultaneously raising the transition temperature to room temperature (289K) from 268K. Similarly, Ao et al. [11] reported an isothermal entropy change of 5.15 J/kg-K near room temperature (297K) for Gd substituted by Tb under a 2 Tesla magnetic field change. Tishin et al. [12] noted significant enhancements in the MCE values of Gd5Si4 when Si was substituted with Gd instead of Tb, resulting in an increased transition temperature to 336K and an isothermal entropy change to 9 J/kg-K for a 0–5 Tesla magnetic field change. Additionally, Piotr Gebara et al. [14] discovered that Gd80Ge15Si5 exhibited a ∆SM of 11.91 J/kg-K at 260K, along with a refrigeration capacity (RCP) of 164 J/kg under a 0-5 Tesla magnetic field change. These findings underscore the diverse and promising magnetocaloric properties of these alloys, positioning them as viable options for various room temperature applications. Among the highlighted alloys, Gd5Si2Ge2B0.075 shows promising potential for commercial magnetic refrigeration applications near room temperature due to its high refrigeration capacity (RC) of 351 J/kg and maximum isothermal magnetic entropy change (∆SM) of 18.5 J/kg-K at ΔH=0–5 T [15]. Furthermore, the properties of Gd5Si2.8Sn1.2 reported by Zhang et al. [16] demonstrate an isothermal magnetic entropy change of 1.69 J/kg-K at 301.5 K under a 1.8 T magnetic field. Moreover, Tishin et al. [12] revealed that the transition temperature and isothermal magnetic entropy value of Ge-added Gd5Si2.06 have been enhanced, with ∆SM reaching 9.5 J/kg-K at 306 K for a 0-5 Tesla magnetic field change. This extensive analysis provides valuable insights into the magnetocaloric properties of various alloys, offering significant potential for diverse applications in room temperature settings.

**Table 2: Magnetocaloric effect in alloys at room temperature**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| S.No | Sample/Composition | ∆Smax (J/Kg-K) | Tc (K) | RCP (J/Kg) | H (T) | Ref |
| 1 | Gd90Ga10 | 7.6 | 285 | 392 | 5 | [9] |
| 2 | Gd50Co50 | 4.6 | 268 | 686 | 5 | [12] |
| 3 | Gd50Co45Fe5 | 3.8 | 289 | 673 | 5 | [10] |
| 4 | Gd60Tb40 | 5.15 | 297 |  | 2 | [11] |
| 5 | Gd5Si4 | 9 | 336 | - | 5 | [12] |
| 6 | Gd5Si2Ge2 | 18.5 | 276 |  | 5 | [13] |
| 7 | Gd80Ge15Si5 | 11.91 | 260 | 164 | 3 | [14] |
| 8 | Gd5Si2Ge2B0.075 | 18.5 | 272 | 351 | 5 | [15] |
| 9 | Gd5Si2.8Sn1.2 | 1.69 | 301.5 | - | 1.8 | [16] |
| 10 | Gd5Si2.06Ge1.94 | 9.5 | 306 | - | 5 | [12] |
| 11 | Mn5Ge3 | 2.3 | 297.5 |  | 2 | [17] |
| 12 | Mn0.7Fe0.3Co0.7Fe0.3Ge | -3.91 | 298 |  | 2 | [18] |
| 13 | Ni43Mn47Sn10.5B0.5 | 17 | 283 |  |  | [19] |
| 14 | Ni41Co7Fe2Mn40Sn10 | 18.9 (22.4) |  | 128 (396) | 2(5) | [20] |
| 15 | Ni41Co6.5Fe2.5Mn40Sn10 | 11.8 (16.8) |  | 99 (313) | 2(5) | [20] |
| 16 | La0.75Sr0.25MnO3 | 9.23 |  |  | 6 | [21] |
| 17 | Fe85Co3Zr5B4Nb3 | 3.55 | 336 |  |  | [22] |
| 18 | Tb (Co0.94Fe0.06)2 | 4.3 | 304 |  |  | [23] |
| 19 | (La1xBix)0.67Ba0.33MnO3 (x = 0 - 0.3) | 6.19(x = 0), 4.79(x = 0.3) | 336(x=0), 229(x=0.3) |  |  | [24] |
| 20 | La0.65Nd0.05Ba0.3Mn1−xCrxO3 (0 ≤ x ≤ 0.15) | 6.19(x=0), 4.79(x=0.3) | 330(x = 0), 275(x = 0.15) |  | 9 | [24] |
| 21 | La(Fe0.94Co0.06)11.83Al1.17 | 24 | 273 |  | 2 | [25] |
| 22 | La0.67Ca0.33MnO6 | 2.75 | 260 | - | 3 | [26] |
| 23 | La0.835Na0.165MnO3 | 2.11 | 342 | 63 | 1 | [27] |
| 24 | La0.813K0.160Mn0.987O3 | 2.10 | 338 | 128 | 1.5 | [28] |
| 25 | La0.78Ag0.22MnO3 | 2.90 | 306 | 38 | 1 | [29] |
| 26 | La2/3Ca1/3MnO3 | 6.4 | 267 | - | 3 | [30] |
| 27 | La0.7Ba0.3MnO3 | 1.6 | 336 | 36 | 1 | [31] |
| 28 | La0.6Sr0.2Ba0.2MnO3 | 2.26 | 354 | 67 | 1 | [32] |
| 29 | La0.7Sr0.3Mn0.98Ni0.02O3 | 7.65 | 350 | 459 | 7 | [33] |

The exploration of magnetocaloric materials reveals a diverse landscape of alloys with remarkable properties for potential applications in various fields. Nguyen et al. [29] highlight La0.78Ag0.22MnO3 as a standout, showcasing a transition temperature of 306 K and yielding a change in magnetic entropy of 2.9 J/kg-K alongside a refrigeration capacity (RCP) of 38 J/kg under a 1 T magnetic field. J. Meera [30] contributes insights on La2/3Sr1/3MnO3, noting its transition temperature at 370 K, with an RCP of 41 J/kg and an change in isothermal entropy of 1.5 J/kg-K at 1 T. Phan et al. [31] focus on La0.7Ba0.3MnO3, revealing a transition temperature (Tc) of 336 K, isothermal entropy change (∆Smax) of 1.6 J/kg-K, and an RCP of 36 J/kg at 1 T. Ayadi's examination of La0.6Sr0.2Ba0.2MnO3 presents values of Tc = 354 K, ∆Smax = 2.26 J/kg-K, and RCP = 67 J/kg at 1 T [32].

Further investigations by Phan et al. [33] explore La0.7Sr0.3Mn0.98Ni0.02O3, unveiling a transition temperature of 350 K, an isothermal entropy change of 7.65 J/kg-K, and an RCP of 459 J/kg at 7 T. Notably, Pr0.58Sr0.42MnO3, examined by D.V. Maheshwar repaka [34], exhibits a transition temperature of 300 K, an isothermal entropy change of 2.33 J/kg-K at 5 T, and an RCP of 65 J/kg.

In addition, remarkable findings emerge from studies on various alloys. For instance, Ni50Mn18.5Cu6.5Ga25 alloy presents a magnetocaloric effect of ΔSM = -81.8 J/kg-K during the reverse martensitic transformation at 303 K with a 9 T magnetic field [35], while Mn-rich alloys like Ni50Mn29Ga21 demonstrate ΔSM = 9.56 J/kg-K at 396 K under 8 Tesla [36]. Aliev et al. [37] observe a variation in magnetic entropy is 4.5 J/kg-K and a Curie temperature of 335 K in Ni2.19Mn0.81Ga alloy at 1.5 T.

Additionally, research on oxide materials offers promising avenues for magnetic refrigeration. CMR (Colossal Magnetoresistance) manganite-based oxides, such as La0.7MnO(3-δ), investigated by Wang et al. [49], reveal a magnetic entropy change around 290 K is 1.32 J/kg-K , and at 1 T the refrigeration capacity is 37 J/kg . In their investigation of Ca-doped LaMnO3, [50] Vonhelmot et al. report that the transition temperature dropped to 267 K when the magnetic field changed from 0 to 3 T, while the magnetic entropy increased to 6.4 J/kg-K Similarly, Phan et al. [51] study La1.6Ca1.4Mn2O7, observing a change in entropy of 17 J/kg-K around 270 K for a change in magnetic field of 5 T. These findings underscore the rich diversity and potential applications of magnetocaloric materials across various temperature ranges and magnetic field strengths.

**Table 3: Magnetocaloric effect in alloys at room temperature**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| S.No | Sample/Composition | ∆Smax (J/Kg-K) | Tc (K) | RCP (J/Kg) | H (T) | Ref |
| 1 | Pr0.58Sr0.42MnO3 | 2.3 | 300 | 65 | 2 | [34] |
| 2 | Ni50Mn18.5Cu6.5Ga25 | 81.8 | 303 | - | 9 | [35] |
| 3 | Ni2.19Mn0.81Ga | 4.5 | 335 | - | 1.5 | [37] |
| 4 | Ni50Mn29Ga21 | 9.56 | 396 | - | 8 | [36] |
| 5 | Ni48Cu1Mn39Sb12 | 9.38 | 291 | 25.9 | 5 | [38] |
| 6 | Ni45Co5Mn36.6In13.4 | 28.4 | 292 | - | 7 | [40] |
| 7 | Ni59.0Mn23.5In17.5 | 2.01 | 246 | 120 | 3 | [40] |
| 8 | MnAs0.9Sb0.1 | 35 | 280 | - | 5 | [41] |
| 9 | Fe88Zr8B4 | 3.30 | 284 | 646 | 5 | [10] |
| 10 | (Fe0.8Mn0.2)3Al | 0.96 | 350 | 400 | 5 | [42] |
| 11 | (Fe70Ni30)97Mo3 | 1.69 | 320 | 440 | 5 | [43] |
| 12 | Fe17Pr2 | 4.5 | 292 | 573 | 5 | [44] |
| 13 | Fe17Y2 | 4.4 | 301 | 533 | 5 | [45] |
| 14 | Fe65Cu35 | 1.04 | 360 | 234 | 5 | [44] |
| 15 | Fe77Ce1Si4Nb5B12Cu1 | 2.39 | 348 | 271 | 5 | [46] |
| 16 | (Fe0.72Cr0.28)3Al | 1.16 | 330 | 305 | 5 | [42] |
| 17 | Fe79B12Cr8Gd1 | 1.42 | 355 | 153 | 1.5 | [42] |
| 18 | Fe79Ce11B6 | 3.90 | 297 | 420.09 | 5 | [47] |
| 19 | La0.7MnO3-⸹ | 1.32 | 290 | 37 | 1 | [49] |
| 20 | La2/3Ca1/3MnO3 | 6.4 | 267 | - | 3 | [49] |
| 21 | (La0.47Gd0.2)Sr0.33MnO3 | 1.93 | 285.9 | - | 2 | [49] |
| 22 | La1.6Ca1.4Mn2O7 | 17 | 270 | - | 5 | [51] |

**5. Bio-Medical applications- Magnetic nanoparticles**

Magnetocaloric materials have garnered significant attention not only for their potential in room-temperature magnetic refrigeration but also for their eco-friendly properties and applications across various technologies. In recent years, there has been a notable surge in exploring the environmental benefits of these materials, along with their diverse applications in fields like heating, refrigeration, and magnetic energy conversion. Particularly intriguing is the expanding interest in utilizing magnetocaloric materials in medical settings, where they hold promise for applications such as controllable drug delivery and magnetic hyperthermia.

One prominent example of medical applications is the magnetic drug delivery system, a technique aimed at precisely targeting drug delivery to specific sites within the body. The concept of magnetic drug delivery has roots dating back several decades, with early experiments conducted as far back as the 1950s and 1960s. Gilchrist's work in 1956 demonstrated the induction of magnetism in lymph nodes near tumors, while Meyers successfully manipulated iron particles in dog veins using magnets in 1963. The idea of magnetic nanoparticles was further developed by Widder, Senyi, and their colleagues in 1970. Subsequent advancements led to the application of magnetic drug delivery in treating conditions like liver cancer by researchers such as Wu, Jones, and Winter.

A significant milestone in the evolution of magnetic drug delivery occurred in 1996 with the initiation of the first clinical trial involving the use of magnets for drug distribution. This trial marked a pivotal moment in validating the feasibility and potential of magnetic drug delivery systems in clinical settings, paving the way for further research and development in this promising field.

The magnetic drug delivery system offers several advantages over conventional drug delivery methods, as outlined in Table 4.

**Table 4: Differences between magnetic drug delivery system and conventional**

**drug delivery system**

|  |  |
| --- | --- |
| **Magnetic drug delivery system** | **Conventional drug delivery system** |
| Do not affect healthy tissues | Affect healthy tissues |
| Toxicity level is lower | Toxicity level is higher |
| Low dose is required | High dose is required |
| Lower side effects | Higher side effects |
| Target specific | Not target specific |
| It is not possible to diagnose and treat with a single agent. | Possible to diagnose and treat with a single agent. |
| High lost | Low cost |

Apart from the above applications there are many uses for magnetocaloric materials, a few of them are mentioned here.

1. Tetrahedral antibodies, chemotherapeutic drug, and magnetic nanoparticles conjugated as the carrier[55].
2. GIT cancer therapy and target imaging using antibody-linked fluorescent magnetocaloric materials[56].
3. Magnetocaloric materials coated with meso-2,3-dimercaprosuccinic acid (DMSA), featuring a carboxylic acid group, have demonstrated the capability to absorb DNA
4. These materials with an iron oxide gold core-shell were employed to detect Escherichia coli[58].
5. The materials can be employed in tumor thermotherapy because they create heat effects when exposed to a changing magnetic field[59]. Hyperthermia and magnetofection are two applications of these materials.

Magnetic drug delivery and hyperthermia are covered in detail since these are two of the most useful uses nowadays.

**5.1. Magnetic drug delivery**

Scientists have introduced an innovative strategy to tackle the problem of rejection linked with synthetic implants, including but not limited to abdominal meshes, joints, stents, biliary and urinary ducts. This involves applying a specialized coating to these implants, comprising multiple layers. The first layer consists of a thin film of negative magnetocaloric material, which is exposed to an external magnetic field and cooled. Subsequently, a drug-absorbing polymer matrix is applied over this layer. Importantly, the polymer matrix is in direct contact with the magnetocaloric material. During the surgical procedure, the entire structure is implanted into the body. When the magnetic field is reduced, the temperature of the polymer decreases, causing it to transition into a liquid state and release the drug at the site of implantation. This targeted drug delivery technique minimizes the impact on the rest of the body, as it only affects the source of inflammation. Moreover, there is a suggestion among researchers to employ magnetocaloric materials for drug delivery purposes, even in surgical procedures. Aleksei S. Komlev has emphasized the potential of using FeRh as a magnetocaloric substance for drug delivery owing to its substantial magnetic entropy change and non-toxic characteristics compared to other iron alloys containing platinum group metals. Additionally, Poly-N-isopropyl-acrylamide (PNIP Am), an implantable component incorporating a drug film, is recognized for its biocompatibility and extensive application in therapeutic dental prosthetics. Integrating such materials into drug delivery systems holds promise for enhancing the efficacy and safety of medical implants and treatments.

Improvements in the creation of functional coatings designed to release bioactive substances under the influence of an external magnetic field are being produced, according to Tishinet al. [2]. In addition, efforts are underway to develop methods for applying these coatings onto implants. A composite material with magnetocaloric characteristics makes comprised the functional coating. Through temperature modulation of the magnetic component, a hydrophilic state transition is induced in a biocompatible polymer that is in thermal contact with the magnetic material. Additionally, a thermal insulating layer is incorporated into the composite coating to reduce heat transfer to the surrounding tissues. The suggested active material carrier has multiple benefits, such as accurate delivery through magnetic carriers and controllable retention/release rate of the active material from the carrier using various materials with different properties in different external conditions like temperature and magnetic field intensity. This approach shows promise in augmenting the effectiveness and safety of drug delivery systems integrated into medical implants [61].

**5.2. Hyperthermia**

Hyperthermia, a treatment method with roots dating back to ancient times, involves deliberately raising tissue temperatures to combat diseases. When cellular temperatures surpass 41°C, several effects occur within the cell membrane and interior:

1. Improved Cell Membrane Fluidity and Permeability: Elevated temperatures increase the permeability of cell membranes and fluidity, potentially facilitating the uptake of therapeutic substances or disrupting cell integrity.
2. Decreased Protein and Nucleic Acid Synthesis: The processes involved in nucleic acid and protein synthesis within cells slow down at higher temperatures, affecting cellular functions.
3. Protein Denaturation and Agglomeration: High temperatures can cause proteins within cells to denature and aggregate, altering their structure and function. Additionally, hyperthermia can harm tumor vasculature, reducing blood flow to the affected area.[61][2].

Cancer therapy has witnessed significant research efforts, particularly in the realm of electromagnetically excitable thermo seeds. Hyperthermia, an established therapeutic approach, encompasses various methods of applying heat to the body. The primary objective of whole-body hyperthermia is to raise body temperature using a variety of methods, including hot water bottles, electric blankets, and hot wax. Regional hyperthermia, on the other hand, targets specific areas or regions of the body for heat application. Regional hyperthermia is a therapeutic approach that targets specific organs or body regions through the use of regional perfusion techniques and external applicators. On the other hand, localized hyperthermia uses electromagnetic wavelengths such as microwaves, radio waves, and ultrasound to concentrate heat on small tumor regions. Applicators that are implanted internally within the targeted region or placed externally on the skin's surface produce these waves. These hyperthermia methods aim to selectively heat cancerous tissues, Hyperthermia, whether applied throughout the body or in localized areas, serves as a method to enhance the efficacy of cancer treatment. This process entails the eradication of malignant cancer cells using an internal heating mechanism.

Reference [3], indicates that the following categories of hyperthermia therapies are depending on the temperature that is maintained inside the tumor:

i. Diathermia, which is defined as a temperature lower than 41°C.

ii. Apoptosis, representing moderate hyperthermia with final temperatures ranging between 42°C and 46°C.

iii. Thermoablation by necrosis, occurring at temperatures exceeding 46°C.

Traditional hyperthermia approaches encounter challenges in achieving sufficiently rapid heating rates. A numerical feasibility investigation referenced as [3] illustrates that this method ideally meets the required heating rate while adhering to the medically tolerated limit expressed as H0\*f < 5\*10^8 Am^-1 s^-1, where H0 and f represent the applied external field and its rotation frequency, respectively.

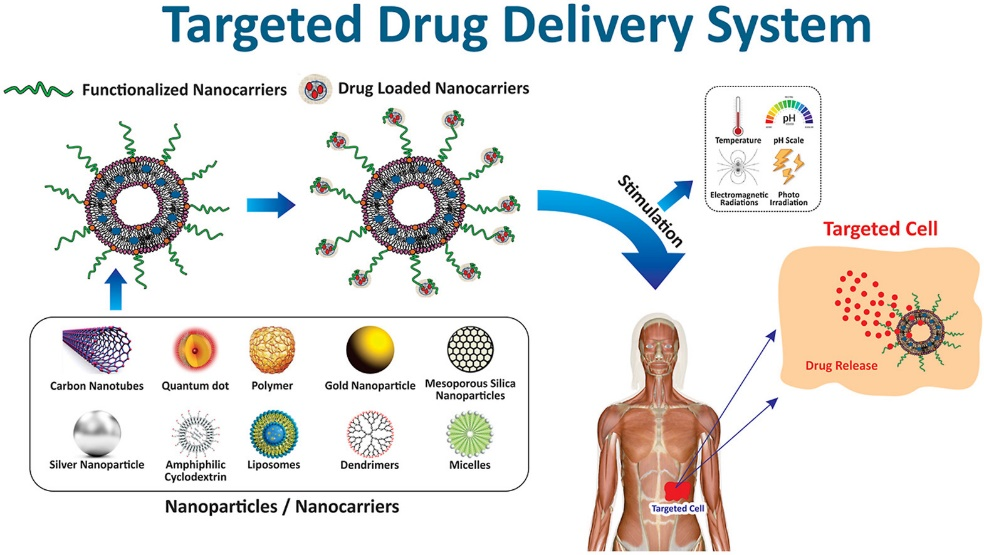
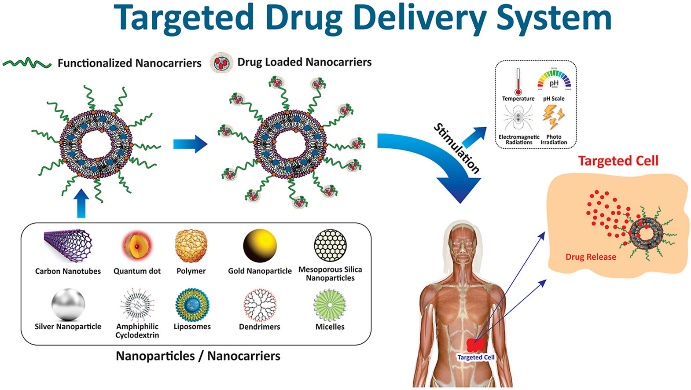


Figure 2: Schematic showing targeted drug delivery in cancer cells

There are two recent innovations in magnetic hyperthermia methods. The first invention, attributed to Russian authors [2], combines principles of magnetocaloric material physics with medical applications, More specifically, this approach targets malignant neoplasms through hyperthermal electromagnetic therapy. In this technique, nanoparticles exhibiting a high magnetocaloric effect (MCE) are introduced into a tumor. These nanoparticles are chosen from materials with a magnetic ordering temperature that closely aligns with human body temperature. Such materials include precious metals, rare-earth elements, as well as specific alloys or intermetallic compounds. These nanoparticles, in low concentrations and nano-sized (e.g., around 200 nm), are uniformly distributed within the tumor, assumed to be spherical. The goal is to heat the tumor to approximately 42°C. This method is often applied multiple times and may be used in conjunction with other cancer treatments such as radiotherapy and chemotherapy.

The second invention marks a departure from conventional methods of magnetic hyperthermia, which usually rely on internal magnetic heating mechanisms such as Brownian and Neel relaxation, as well as hysteresis effects. In this innovative approach, a substantial quantity of nanowires is uniformly dispersed within a biocompatible gel or fluid. This mixture is subsequently injected into the cancerous tumor. Upon application of a rotational magnetic field, these nanowires rotate within the fluid. friction within the boundary layer of the nanowire's fluid. This frictional interaction produces a robust heating effect, ultimately elevating the tumor's steady-state temperature and effectively destroying malignant cancer cells. While this method does not involve the use of rotating nanowires as "Nano scalpels" to directly cut tumor cells, the heating effect induced by fluid friction serves as the primary mechanism for tumor destruction.

**6. Future work in medical field**

Utilizing Magnetocaloric Effect (MCE) for hyperthermia treatment can be further optimized by enhancing the heating rate, enabling the concurrent operation of multiple magnetic heating mechanisms to destroy cells. Additionally, it is feasible to engineer a magnetic field variation within the nanowires, thereby inducing MCE. This approach offers the added benefit of the magnetic phase transition facilitates temperature stabilization. This transition leads to an increase in effective specific heat and enhanced thermal capacity, contributing to temperature control within the tumor during the hyperthermia treatment.

**7. Conclusions**

Magnetocaloric materials offer enhanced cooling capabilities and contribute to environmental protection by reducing reliance on various gases. The advancement in magnetic refrigeration technology, particularly in room-temperature applications, has garnered global recognition. This transformative technology is poised to supplant conventional gas compression cooling (CGC) methods in the foreseeable future. The discovery of exceptional magnetocaloric materials has opened up novel opportunities for their utilization as alternative working substances in active magnetic refrigerators across different temperature ranges. There is a growing focus on medical applications, particularly in leveraging magnetocaloric materials composed of thermo-sensitive polymers and magnetic components with significant MCE values. Indeed, these materials hold significant promise for various biomedical applications. By leveraging their magnetocaloric properties, they can provide localized cooling within the human body, which is beneficial for therapeutic purposes such as reducing inflammation or managing pain. Additionally, their ability to respond to external magnetic fields makes them valuable candidates for controlled drug delivery systems. By precisely guiding drug-loaded nanoparticles to specific target sites, such as tumors, using external magnets, these materials offer advantages over conventional drug delivery methods. This targeted approach can enhance the efficacy of treatment while minimizing side effects on healthy tissues, representing a significant advancement in medical technology. While magnetic drug delivery is still in its nascent stage, ongoing efforts aim to transition it from laboratory research to clinical practice through the development of improved magnetic drug delivery systems.

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