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Quantum Dots in Precision Oncology: Emerging Strategies for Targeted Cancer Therapy

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ABSTRACT: Quantum dots (QDs), or nanocrystalline semiconductors, are distinguished by their nanoscale dimensions—generally between 2 and 10 nm—and their exceptional optoelectronic properties derived from the quantum confinement effect. Unlike traditional bulk semiconductors, quantum dots exhibit size-dependent behaviours: altering their size or shape enables tuning of their absorbance and emission spectra, quantum yield, and energy levels. Their discrete electronic states are reminiscent of atomic spectra, earning them the moniker "artificial atoms." These features—such as tenable photoluminescence, robust emission, and pronounced resistance to photobleaching—make QDs highly valuable for biomedical applications, especially in cancer diagnostics, imaging, and theragnostic. Recent advances in QD synthesis have focused on two principal strategies: top-down and bottom-up methodologies. Top-down approaches like electron beam lithography afford precise control over dot placement and dimension, but struggle with scalability. In contrast, bottom-up methods—including microemulsion, sol-gel processing, and colloidal precipitation—provide greater control over particle size, enable uniformity, and are more conducive for biomedical-grade scale production. The introduction of core–shell and multi-shell architectures has markedly advanced QD photostability, diminished non-radiative surface defects, and expanded their application range. These strategies have also facilitated the fabrication of safer, heavy-metal-free quantum dots, such as those based on carbon or silicon, which promise reduced toxicity without sacrificing desirable optical features. To translate QDs into biomedical contexts, surface engineering is pivotal. QDs synthesized by standard

methods are generally hydrophobic and prone to aggregation, limiting their aqueous stability and biocompatibility. Functionalization techniques—including ligand exchange, salinization, polymer encapsulation, and PEGylation—render QDs soluble in biological media, extend circulation times, reduce protein adsorption, and minimize acute toxicity. These surface modifications additionally permit the conjugation of drugs, targeting molecules, or responsive linkers, enabling QDs to serve as multiplexed nanoplatforms for drug delivery and biosensing. Within oncology, quantum dots have emerged as next-generation fluorescent biomarkers. Their high quantum yield, broad absorption, and sharp emission, and stability against photobleaching allow for real-time tracking of cancer progression, multiplexed tissue imaging, and sentinel lymph node mapping. Through functionalization with tumour-specific ligands (antibodies, peptides, or aptamers), QDs can selectively accumulate in cancerous tissues, enhancing imaging sensitivity and specificity. Indium phosphide and graphene-based QDs conjugated with targeting moieties, for instance, have demonstrated strong tumour-localized fluorescence in vivo. Carbon, silicon, and black phosphorus-based quantum dots offer alternative solutions with reduced heavy metal risks, adapting QDs for safer clinical translation. Beyond diagnostics, QDs are being integrated as multifunctional therapeutic carriers: they can deliver anticancer agents, nucleic acids, or phototherapeutic substances to tumour sites. Covalent and non-covalent conjugation chemistries—such as EDC-NHS coupling and click-linkage—enable stable drug–QD assemblies with site-specific, stimuli-triggered release profiles (e.g., pH, redox). Nanoconjugates equipped for photodynamic or photothermal therapies uniquely merge imaging and treatment capabilities within a single construct, allowing both real-time process monitoring and targeted therapy delivery. The encapsulation of QDs within polymeric or PEGylated matrices further advances systemic stability and prolongs blood circulation, which is vital for therapeutic efficiency and safety. Despite surging interest, concerns regarding QD toxicity persist, particularly for cadmium-, lead-, and indium-based nanocrystals. Risks include heavy metal ion leakage, chronic bioaccumulation in tissues, and unforeseen effects on organ systems. Several strategies, such as robust core–shell designs, silica or polymer coatings, and development of non-toxic alternatives, seek to mitigate these effects. However, extensive research into pharmacokinetics, biodistribution, long-term toxicity, and clearance mechanisms is imperative before widespread clinical adoption. Looking ahead, quantum dot technology is being geared towards even more sophisticated functionalities: integration with immune-modulatory agents, gene therapies, multimodal imaging techniques, and biosensors for real-time disease monitoring. The convergence of QDs with smart analytics and personalized medicine heralds a future where simultaneous diagnosis, therapy, and monitoring are achieved on a single nanoplatform. Ongoing innovation in material science, clinical safety, and application engineering positions QDs as central players in the evolving field of cancer nanomedicine.

INTRODUCTION

Quantum dots (QDs) are extremely adaptable for a variety of cancer treatment uses. The distinctive electronic structure of QDs, which confers functional characteristics, is one of its primary characteristics. Notably, they can be employed for fluorescence diagnosis in biosensing and bioimaging because of their powerful and controllable photoluminescence. Furthermore, QDs show a remarkable ability to load cargo, which makes them perfect for applications involving medication administration. Furthermore, QDs are intriguing candidates for cancer-killing methods like photodynamic therapy because of their capacity to absorb incident radiation.

We now have a detailed understanding of the facts regarding nanocrystals in applied research, which has allowed us to see the potential of nanoparticles and their negative impacts in the present era.Nanocrystals are nanomaterials that can be used in advanced research and therapeutic activities. They are small particles, usually smaller than 100 nanometres, that have a crystalline structure throughout their volume, which means that their atoms are grouped in a repeating pattern. The QDs are ideal for drug delivery applications because of their exceptional cargo loading capacity, yet they have the same features. Additionally, their abilityto absorb incident radiation makes them appealing candidates for cancer-killing techniques such as photodynamic therapy. The aim of this extensive review is to show how they help in the treatment of cancer

The purpose of this extensive analysis is to present a current and comprehensive description of the most recent discoveries in the application of QDs as new and versatile biomaterials. In addition to describing technical advances in QD synthesis, this review seeks to elucidate QD biological, electrical, and physicochemical properties. the biological, electrical, and physicochemical characteristics of QDs. It also highlights the substantial potential of QDs in the treatment of cancer by thoroughly examining the advancements made in their use for diagnosis based on biosensing, bioimaging, and therapy applications such as drug administration and necrosis. The paper also discusses the present drawbacks of using QDs in cancer treatment and offers insightful advice for the future, which will help this sector develop further. This review functions as an authoritative and educational resource by providing a thorough and organized summary of aresource that can direct upcoming studies and promote ongoing advancements in the field of QDs for cancer treatment.

Drug delivery systems, bioimaging, and biosensing are just a few of the medical and healthcare domains where nanocrystals have found application. Biopolymer nanoparticles are also used in packaging materials, edible films, wastewatertreatment, and luminous biosensors. Semiconductor crystals with sizes ranging from 2 to 10 nanometres are known tobe quantum dots (QDs). They can emit a broad spectrum of strong light that is resistant to photobleaching. They are essentially categorized by their size, ligands, shape, structure, and core type. Cadmium, indium, and carbon are common cores for quantum dots. Chalcogenides like tellurides, sulphides, and selenides encapsulate them.

Because of the deterioration of the materials that make them up, core-only quantum dots have shown low stability. For instance, exposure to oxidizing conditions causes the selenium-rich surface layer of cadmium selenide (Cd se) QDs to oxidize, jeopardizing the structural integrity and perhaps causing cadmium ion leakage. The capacity to limit electron mobility in one or more spatial dimensions is a crucial feature in biomedical science, and quantum dots have a special quality that nanoparticles do not have. This capability is known as quantum confinement. where it was used as a method for the delivery of cancer drugs. Potential toxicity, stability, pharmacokinetics, and targeted specificity are among of the difficulties they face in cancer treatment.

However, compared to nanoparticles, quantum dots (QDs) offer more effective drug delivery for cancer targeting. The illness has a lot of responsibilities and consequences. However, they are more capable of delivering drugs than nanoparticles. All things considered, QDs provide a variety of qualities that could lead to improved therapeutic results and less side effects for a range of cancer types, making them a promising new frontier in cancer treatment. This article discusses quantum dots and how they are used in cancer treatment. They provide numerous benefits in terms of medicine and drug delivery. The latest generation of nanotechnology is being revolutionized by its ability to be used in the biomedical phase. Where they are mostly utilized in vast ways, we will examine how this technology has made an impact on cancer therapy.

Characteristics of quantum dots:

- The quantum confinement effect, which is useful for higher energy levels, is demonstrated by quantum dots. it is beneficial for bioimaging
- They have optoelectronic behavior, meaning they can both emit and absorb
- Their bioimaging capabilities allow them to create vivid colors in tiny bands.
- They are useful for medication delivery because of their huge surface area and various ratios.
- Drug administration and imaging feedback are two simultaneous capabilities of quantum dots.

Importance of the characteristics in cancer therapy:

The characteristics of the quantum dots help in various aspects, and they have different cytotoxicity profiles while treating and using them in therapy, the quantum dots demonstrate the capability of having numerous characteristics.

While the nanoparticles are becoming a new revolution in the medical industry, the quantum dots have been a key to the treatment and diagnosis of various diseases, and they have become a true upgrade in the therapy of cancer by following their characteristics.

CLASSIFICATION OF QUANTUM DOTS

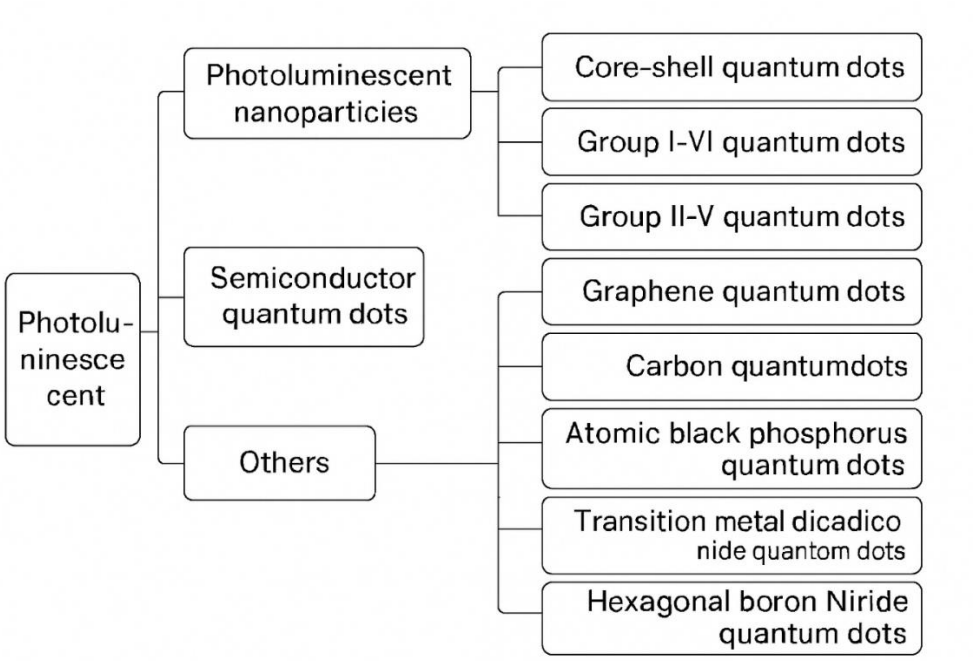

Figure:1 Classification of quantum dots

The quantum dots are classified into three classes based on their photoluminescent property. The difference in properties mainly the semiconductor quantum dots,exhibits the photo stability and photo emission. Smaller quantum dots with a diameter of 2-3 nm have lower emission capability. Flexible surface chemistry opens up a variety of approaches for QD surface customization. Third, due to their photophysical properties, QDs can monitor drug release and drug transport in real time. Carbon dots are roughly 10 nm in size, have a low molecular weight, and have photoluminescent properties.Where they are nano carriers as well as smart particle's they are easily capable of drug delivery.possess Surface functional groups include carboxyl (-COOH), amino (-NH_2), and hydroxyl (-OH).'

which offer accessible sites for surface conjugation. Their low cytotoxicity, good biocompatibility, and inherent fluorescence emission make them ideal for use in cellular and tissue bioimaging, as well as targeted drug administration. In current ages, the combination of nanotechnology with oncology has resulted in significant advances in cancer diagnosis and treatment. They havethe potential to be effective nanocarriersfor their strong applications in targeted cancer therapy.which offer accessible sites for surface conjugation. Their low cytotoxicity, good biocompatibility, and inherent fluorescence emission make them ideal for use in cellular and tissue bioimaging, as well as targeted drug administration. In newages, the combination of nanotechnology with oncology has resulted in significant advances in cancer diagnosis and therapy. Quantum dots (QDs) have emerged by way of effective nanocarriers with promising applications in targeted cancer therapy.

This review aims to outline the progress made in using QDs as drug delivery platforms across diverse cancer types, address current obstacles, and investigate possible future paths in this quicklygrowing field.This review intends to outline the progress made in using QDs as drug delivery platforms across diverse cancer types, address current obstacles, and investigate possible future paths in this rapidly growing field.

Absorbance property in cancer therapy:

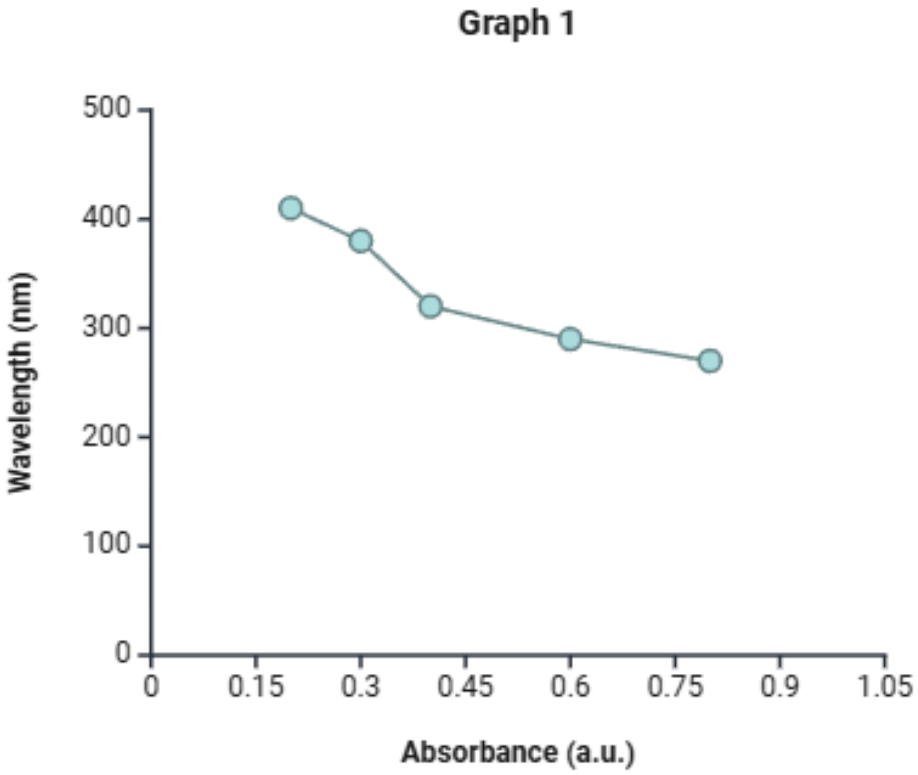

Figure 2: UV-VIS spectra absorption of quantum dots

The ability to absorb photons, which are light energy from the environment.When the energy of an incoming photon equals the change between the ground and excited electronic states, an electron is promoted to the next higher energy level. When subjected to radiation, carbon quantum dots (CQDs) show clear optical absorption peaks that are caused by these electronic transitions. UV-VIS absorption spectra of CQDs made from dissimilar marine polymers. The existence of double-bond carbon and single-bond carbon linked to the sp^2-hybridized carbon atoms within the central structure of CQDs is responsible for the inherent $\pi \rightarrow \pi^*$ transitions. Depending on the type of precursor utilized to create the CQDs, the location of the $\pi \rightarrow \pi^*$ transition peak may experience a red shift.

For example, CQDs produced from chondroitin sulphate, carrageenan, chitosan, and agarose show absorbance peaks at roughly 230, 240, 270, and 287 nm, in that order.

Photoluminescence Properties in Cancer Therapy:

When external energy reacts to incident photons, it causes the emission of light (photons);this phenomenon is known as photoluminescence. The term photoluminescence refers to the energy that a material absorbs from its environment. When an electron in the valence shell becomes excited, it transitions to the conduction band. This process arises when the incident photon's power equals or over the limitof the material's bandgap. This energy is absorbed by the substance. This phenomenon occurs when the energy of the incident photon exceeds the material's bandgap. As the electron returns to its ground state, it eventually emits energy in the form of a photon. Carbon -quantum dots (CQDs) emit light foundedbased on their size.

Because of their greater band gaps, smaller CQDs require more energy to excite electrons and emit more energy-dense light. The colour of the light emitted by CQDs shifts from blue and green to yellow and red as their bandgap widens with decreasing size, releasing energy as photons.Carbon quantum dots (CQDs) emit light based on their size. Smaller CQDs have greater band gaps, requiring more energy to excite electrons but emitting more energy.

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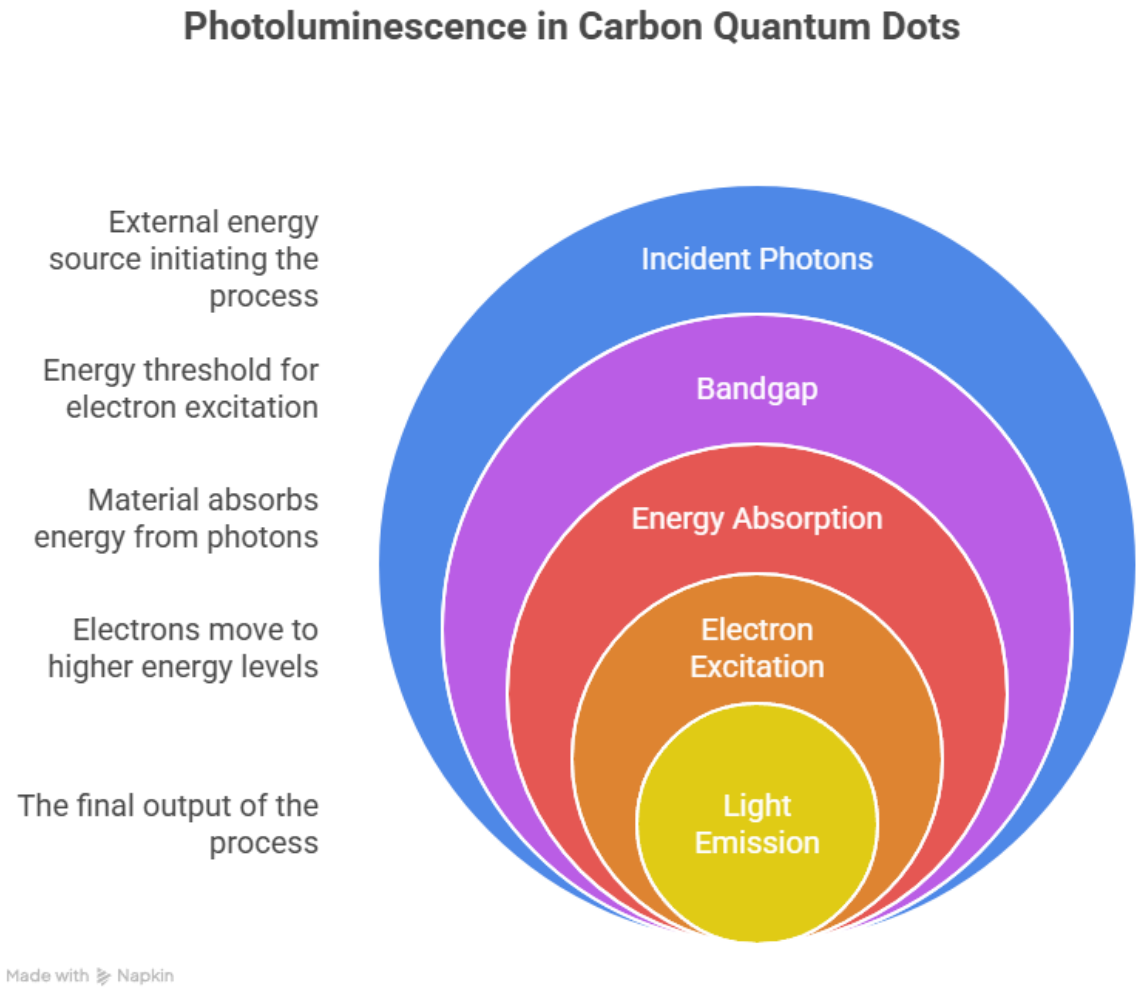

Synthesis of QDs:

To satisfy particular optical criteria, QDs must be meticulously created. The different types of synthesis processes they mainly used for the synthesis of the quantum dots

1. Top-Down approach
2. Bottom-up approach

Top-Down Approach:

Using thetop-down method, bulk semiconductor materials are ablation-formed to create QDs. This covers procedures like focused ion beam, reactive ion etching, and electron beam lithography. These procedures create QDs that have a diameter of about 30 nm. These procedures do have certain drawbacks, too, namely the incorporation of contaminants during synthesis. big quantum dots are primarily produced on a large scale using this technique.

QDs are produced by ablation of bulk semiconductor materials in a top-down manner. This covers techniques like electron beam lithography, reactive ion etching, and focused ion beam. These techniques produce QDs with a diameter of about 30 nm. One of the downsides of these techniques is that they incorporate contaminants during synthesis. Large-scale production of large quantum dots is mostly accomplished using this technique.

1. Electron Beam Lithography (EBL)
2. Reactive Ion Etching:

3. Focused Ion Beam (FIB)

1.Electron Beam Lithography (EBL):

Electron beam lithography (EBL) patterns the surface of a resist (an electron-sensitive substance) with a focused electron beam. The resist may contain a positive or negative polymeric component. Because the electron beam changes the solubility of the resist when immersed in a solution, only the exposed or non-exposed sections of the resist can be extracted.

2.Reactive Ion Etching:

During the dry etching process, a sensitive gas species is pumped into an etching chamber, and radiofrequency radiation is used to break up the gas molecules into reactive fragments, resulting in plasma. These high-powered species collide with the surface and react, resulting in a volatile reaction product. The surface gradually erodes as a result. The surface can be protected from etching by utilizing a disguise design.

3.Focused Ion Beam (FIB):

The focused ion beam technique enables the manufacturing of QDs with extraordinarily high lateral precision. Sputtering the surface of the semiconductor substrate uses highly concentrated beams from a metal ion source (Au/Si, Ga). The dimensions, shape, and interparticle separations of QDs are determined by the size of the ion beam. The focused ion beam method permits QD manufacturing with extraordinarily high lateral accuracy. A metal ion source (Au/Si, Ga) emits highly focused beams that sputter deposit on the surface of a semiconductor unit substrate. The dimensions, shape, and inter-particle separations of QDs are all affected by the size of the ion beam.

BOTTOM-UP APPROACH

The bottom-up technique is used to assemble (precipitate) small units into the proper size and shape. This process involves chemical breakdown, growth, and nucleation. Numerous technologies, which are further separated into vapor-phase and wet-chemical approaches, are used to manufacture QDs.

1. Wet-chemical methods includesol-gel
2. microemulsion.

1.Wet Chemical Methods include Sol–Gel:

Methods with Wet Chemicals Sol-Gel: Sol-gel techniques are commonly utilized to produce QDs. In a base or acidic medium, the process yields a sol (a solution or suspension) of a metal precursor salt (acetates, nitrates, or alkoxides). The technique comprises three steps: growth (gel formation), condensation (sol formation), and hydrolysis. When the metal precursor hydrolyses and condenses in the solvent medium, a sol is formed, which formerly expands or polymerizes to create a network (gel).

2.Microemulsion Process:

The microemulsion procedure is an effective way to produce QDs at normal room temperature. Two oil-based aqueous phase microemulsions with different semiconductor chemical components are formed. During gradual normal temperature mixing, the tiny droplets collide and combine, forming a combination that forms QDs within the minor water droplets. Another option is to use a type of oil-in-water emulsion with semiconductor components in the oil phase. Water has also been replaced with alcohol.

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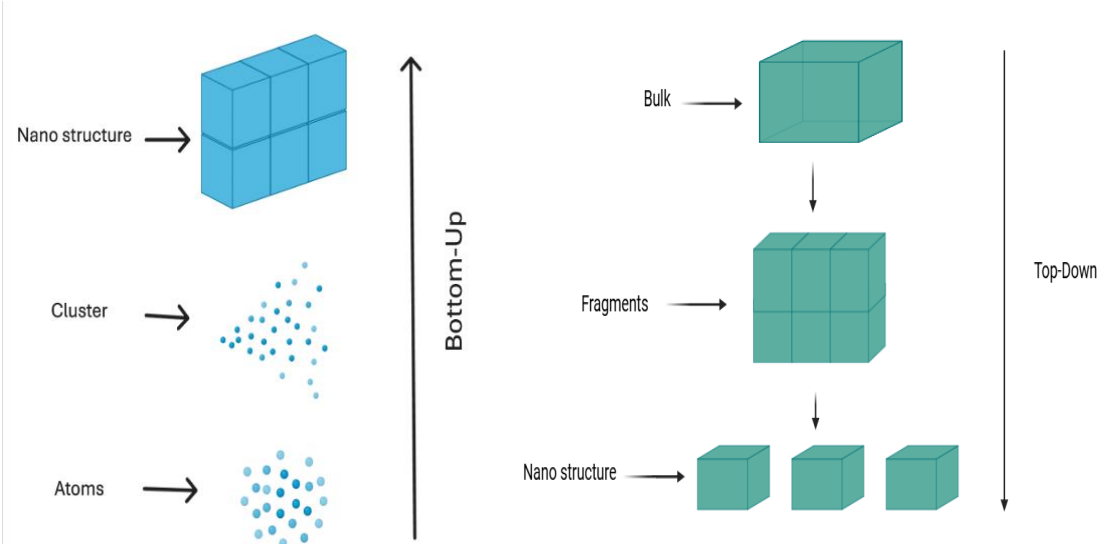


APPROACHES TO DRUG CONJUGATION ONTO QDS:

Drugs are conjugated with QDs using a range of complex techniques, each with its own advantages. Improved therapeutic results, prolonged release, and accurate medication administration are made possible by these techniques. The main tactics used are listed below.

COVALENT CONJUGATION LINKING:

A dependable method for attaching medicinal molecules to QDs is covalent bonding, which guarantees strong and long-lasting bonds. This strategy facilitates focused and prolonged drug release, which increases the therapeutic efficacy of medications. QDs' free amino and carboxylic groups are frequently covalently linked to homologous groups on medicines or proteins. Covalent linkage can occur via a number of mechanisms, including the following:

- The conjugation of biomolecules with -NH2-containing QDs is a typical approach for introducing the thiol group into molecules. SMCC [Sulfosuccinimidyl-4-cyclohexane-1-carboxylate] is a popular reagent.
- Biomolecule conjugation with -NH2-containing QDs is a typical approach that uses the thiol group on molecules. SMCC is a commonly used reagent. Amino group-containing QDs associate with proteins,peptides, receptors, and antibodies.
- By forming disulfide bonds with sulphur-containing substances, including amino acids, thiol-containing QDs can increase the solubility of hydrophobic QDs. By forming disulfide bonds with sulphur-containing substances, including amino acid chains, thiol-containing QDs can increase the solubility of the hydrophobic QDs.
- Likewise, epoxide-covering QDs react with amine, thiol, or hydroxyl molecules to form long-lasting secondary amine, thioether, or ether connections. Similarly, epoxide-containing QDs react with hydroxyl molecules to form long-lasting secondary amine, thioether, or ether connections.

Non-Covalent Conjugation:

Because of its adaptability and reversibility, non-covalent conjugation is a desirable approach. It makes it possible for different medications to bind to QD surfaces lacking changing their chemical makeup, maintaining the drug's structural integrity and bioactivity. forces that are not covalent. Because of its adaptability and reversibility, non-covalent conjugation is a desirable approach. It makes it possible for different medications to bind to QD surfaces without changing their chemical makeup, maintaining the drug's structural integrity in addition to bioactivity.

Click Chemistry:

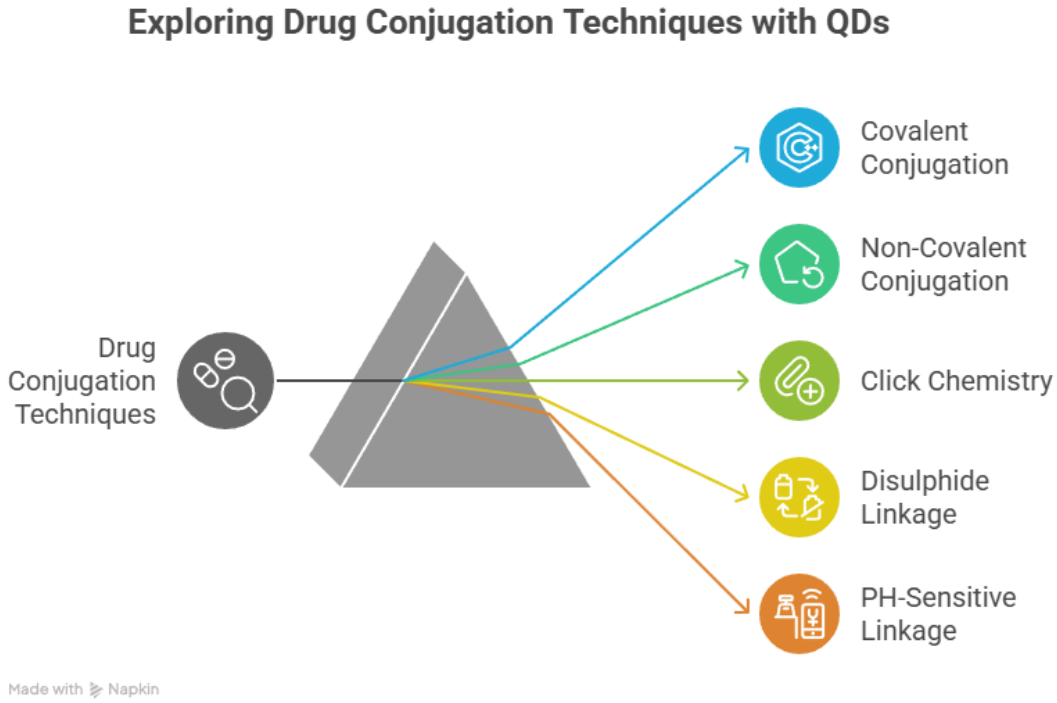
Click chemistry allows for precise attachment without interfering with other components by leveraging highly selective and well-organized interactions between specific functional groups of QDs and medications. The bio-orthogonal property of click chemistry is used in drug administration onto QDs to enable precise control over drug distribution, hence increasing the therapeutic potential of the drug delivery system. The concept of bio-orthogonality ensures that a reaction can occur within physiological parameters such as pH and temperature. Furthermore, click chemistry allows for greater versatility in drug linking approaches by responding to a wide spectrum of drug molecules and quantum dot surfaces.

Disulphide Linkage:

Disulfide bonds are used in the direction of bind medicines on QD surfaces, allowing for controlled release in the intracellular milieu. This method assures that conjugated drug molecules remain stable in oxidizing environments while also delivering drugs to cancer locations.

PH-Sensitive Linkage:

Another unique method that could improve the localized therapeutic effect while reducing systemic exposure is to use pH-sensitive linkers to bind medicines to QDs and explicitly release them in the acidic tumourmicroenvironment. Because of the pH-sensitive link, the drug remained stable within the CQDs until it reached the TUMOR location. This technique ensured that the treatment had the best therapeutic efficacy possible by efficiently preventing premature drug release and degradation. The conjugated drug delivery method substantially suppressed TUMOR growth more than free drug formulations, demonstrating the advantages of pH-sensitive drug conjugation.



Surface Functionalization of QDs:

The biomedical potential of quantum dots (QDs) relies heavily on surface modification. As-synthesized QDs are usually hydrophobic, which limits their dispersion in biological media, decreases cellular uptake efficiency, and increases the risk of cytotoxicity. To make them suitable for applications such as drug delivery, imaging, and diagnostics, their surfaces must be engineered to become hydrophilic, biocompatible, and chemically versatile. Functionalization strategies involve coating, encapsulation, or ligand modification to improve stability, water solubility, targeted binding, and reduced toxicity. Commonly employed approachescontain ligand exchange, surface salinization, amphiphilic polymer coating, and then microsphere encapsulation.

Ligand Exchange:

In this widely used method, the hydrophobic ligands present on QD surfaces,such as pertri-octylphosphine oxide (TOPO), are replaced with hydrophilic molecules. This process generates stable aqueous suspensions of QDs.

- Thiols (-SH) are the most common anchoring groups, often employed in compounds such as mercaptoacetic acid (MAA).These molecules contain carboxyl (-COOH) groups that enhance water solubility through hydrogen bonding and electrostatic repulsion at physiological pH (5–12).

- Hydrophilic polymers, including polyethylene glycol (PEG), are also used to further extend solubility via steric hindrance, thereby preventing aggregation.

Reported outcomes: Ligand-exchanged QDs generally retain small hydrodynamic diameters, which remains advantageous for fluorescence resonance energy transfer (FRET) applications. Though one trade-off is a decrease in fluorescence quantum yield, which has been noted in several revisions.

Surface Salinization:

Surface salinization involves creating a silica shell around QDs, making it one of the most robust modification techniques.

- Initially, hydrophobic groups are replaced with silane derivatives (e.g., mercaptopropyl trimethoxy silane, MPS) that generate silanol groups on the QD surface.
- This step is tracked by more silica growth, which is able to incorporate functional silanes such as aminopropyl silanes (APS), PEG-silane, or phosphonate-based silanes to impart desired chemical functionalities.
- The silica shell not only enhances stability, dispersibility, and biocompatibility, but also provides terminal groups (thiol, phosphate, methyl) for further conjugation with biomolecules.

Advantages: The highly cross-linked silica coating stabilizes the QDs, improves fluorescence, and offers a versatile platform for subsequent modifications.

Amphiphilic Ligands:

Another approach is the use of amphiphilic polymers, which preserve the original hydrophobic surfactants (TOP/TOPO/HDA) on the QD surface while simultaneously enabling water dispersibility.

- The hydrophobic alkyl chains of the polymer interact with the QD surface ligands, while the hydrophilic domains (carboxylic acid or PEG chains) extend outward, ensuring solubility in aqueous media.
- Crosslinking within the polymer matrix enhances robustness and prevents desorption of the coating.
- QDs encapsulated with amphiphilic polymers typically maintain up to 90% of their initial brightness, demonstrating improved colloidal stability.

Advanced strategy: Carolina and Wolfgang developed pyridyl-modified amphiphilic polymer ligands (Pym-Puma), which overcame limits such as reduced photoluminescence quantum yield and susceptibility to oxidative damage. These modified ligands provided better photostability and water dispersibility while maintaining high quantum yield.

Microsphere Coating:

Encapsulation of QDs within microspheres is another promising technique for biomedical use, particularly for drug delivery and imaging.

- QDs can be incorporated into microspheres using approaches such as emulsion polymerization or the reverse microemulsion method.
- They may also be physically entrapped, electrostatically bound, or dispersed within a polymeric scaffold or matrix.
- The microsphere shell serves as a protective barrier, minimizing direct exposure of QDs to the biological environment while simultaneously allowing for controlled release and functionalization.

Applications: Microsphere-encapsulated QDs have been widely explored for biosensing, diagnostic imaging, and composite nanostructures where the microspheres act as scaffolds or adhesive carriers for biomedical systems.

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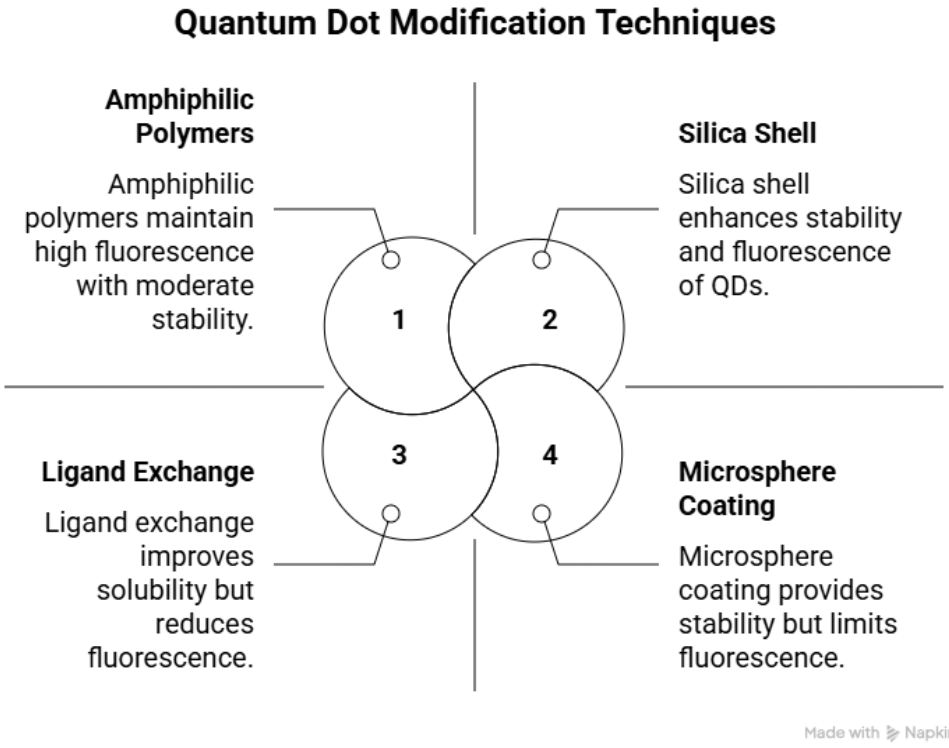
Table 1: Advantages and disadvantages of surface modification technique:

Surface Modification Techniques	merits	demerits
Ligand exchange	Dealing out simplicity and tiny QD size.	QD core oxidation increases the probability of QD photophysical property degradation inside an aqueous environment (lower PLQY).
Surface salinization	Controlling the thickness of the silica shell allows you to fine-tune the QD's reply to light. Progresses QDs' PLQY and boosts photochemical stability.	QD combination in aqueous solution with large hydrodynamic dimensions.
Amphiphilic ligands	Additional chemically steady. Improved colloidal stability. Excellent biocompatibility and robust, consistent fluorescence signals	Size enlargement can cause Surface faults
Microsphere coating	Increase the stability of QD, increase fluorescence, Capable of successfully concealing QD toxicity	It prevents a homogeneous microsphere from forming. Diminished PLQY QD aggregation occurs when significant concentrations of QDs are encapsulated.



ABILITY OF QUANTUM DOTS IN TUMOUR IMAGING

The ability of the quantum dots in bioimaging of cancer cells helps in cancer therapy. There are some studies on quantum dots' ability in bioimaging, such as

FOR EXAMPLE,

Yao et al. used sulfonic-graphene QDs to target tumour cells in vivo. They demonstrated that the sulfonic-GQDs effectively infiltrated cancer cells through the plasma membrane without affecting any bio-ligand, which they attributed to the high interstitial fluid pressure. They also discovered that after injection, tumour-bearing rats fluoresced with sulfonic-GQDs at 470 nm. Sulfonic-GQDs accumulated in the tumour place within 30 minutes of injection and dissipated one day advanced. This work found that sulfonic-GQDs, which are poorly dispersed in healthy tissues, can target the nuclei of tumour cells in vivo.

Wu et al. developed a novel plancounter totumour cells in a separate study. They adapted near-infrared fluorescent indium phosphide (In) QDs with an anti-VEGFR2 monoclonal antibody and coupled an inhibitor of miR-92a to VEGFR2-InP QDs. It is reported that miR-92a promotes the appearance of the tumour suppressor p63. According to their results, the functionalized Nanocomposite targeted tumour angiogenic cells by demonstrating higher NIR fluorescence intensity at the tumour site, which neededto be grouped due to better penetrability and preservation effect. Accumulated due to improvedpenetrability and retaining effect. Furthermore, they investigated the in vivo prevention of tumour growth using nude mice infected with K562 cells. In QDs or miR-92a, which demonstrated considerable inhibition. Inclusive, the created approach has the potential to deliver a novel and promising chemotherapeutic technique for tumour cells.

HOW BIO IMAGING HELPS IN CANCER DETECTION

Triple-negative breast cancer (TNBC) spreads rapidly and is associated with metastases and recurrence. Less than 30% of patients receiving chemotherapy survive, showing that the treatment is ineffective. Zhao et al. developed biomimetic black phosphorus QDs (BBPQDs) coated with cancer cell membranes for anti-PD-L1 immunotherapy and tumour-targeted photothermal treatment (PTT). The BBPQDs' stability post encapsulation in the cancer cell membrane indicated their potential to actively target and enrich tumours.Following that, BALB/c mice with 4T1 tumours were given intravenous injections of Cy5.5-labeled BBP QDs to investigate tissue distribution and tumour targeting. Following injection, the BBPQDs demonstrated considerably stronger fluorescence intensity than the Cy5.5-labeled BPQDs. Furthermore, 72 hours later, the BBPQDs showed a better tumour than the Cy5.5-tagged BPQDs. Furthermore, the BBPQDs showed robust tumour targeting, considerable aggregation, and good retention at the cancer site after 72 hours. In addition to efficiently destroying tumours, the BBPQDs had remarkable photothermal properties and were able to induce T cell activation and dendritic cell maturation. Through immunological Together, the memory effect, BBPQD-mediated PTT, and PD-L1 inhibited tumour development and recurrence.

Huang et al. used photobleaching to manufacture stable fluorescent CQDs. The generated CQDs proved viability in bioimaging mice with Smmc7721 tumour cells, with a reported quantum yield (QY) of around 13% at 365 nm excitation. CQDs were injected intravenously at 0.2 g/mL concentration. The distribution of the CQDs was determined at various time points. According to the study, CQDs accumulated at the tumour location after three hours, and a fluorescence signal appeared five minutes after injection. It was reported that the CQDs had accumulated completely after 12 hours. The CQDs appeared to be biocompatible and might be used for long-term imaging. Furthermore, the findings revealed that CQDs were collected in the liver, kidney, and tumour.

OPTICAL CHARACTERISTICS

Although QDs' distinct optical properties make them a desirable fluorescent probe, particularly in bioimaging, their application has been limited because of possible toxicity, such as those containing dangerous heavy metals. For in vivo imaging, Yaghan et al. created a biocompatible, heavy metal-free, and improved photoluminescence The potential of these metal-free QDs for in vivo axillary lymphatic mapping applications was examined. The QDs showed consistent photoluminescence 24 hours after being injected into the rats' paws. They mostly gathered in the localized lymph nodes, with very little gathering in the liver. They are appealing for in vivo tumour imaging due to their low inherent toxicity.

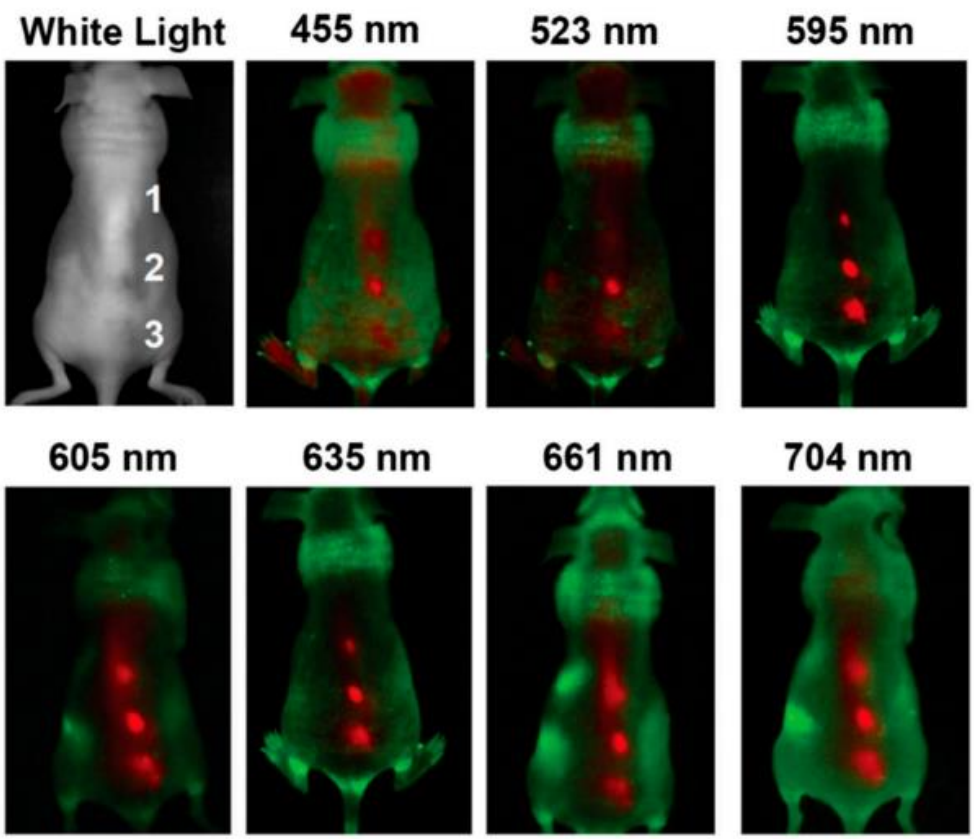


Fig: The image shows how quantum dots help in bioimaging

ABILITY OF QUANTUM DOTS IN DRUG DELIVERY IN CANCER THERAPY

QDs are among the several nanoparticles (NPs) that have been thoroughly investigated for drug delivery applications. The reported decrease in systemic side effects and rise in antitumor efficacy are due to the efficient nanoparticle entrapment of anti-cancer drugs and the control of distribution in cells and tissues. It has been claimed that the cytotoxicity, lack of selectivity, and multidrug resistance of traditional cancer treatments can be addressed by employing nanoparticles as drug delivery vehicles.

Furthermore, it has been found that these nanocarriers facilitate the delivery of medications and enhance their biodistribution. They can target tissues or tumour cells as drug carriers, safeguarding the medication during transit. Drug delivery can occur actively when a drug delivery system (DDS) is combined with peptides and antibodies linked to lipids or receptors at the target location, or passively. In general, nanoparticles make ideal nanocarriers for targeted drug delivery. They are decent options because of their controlled drug release, accumulation at the tumour site as a result of the enhanced permeability and retention (EPR) effect.They have abilitiesfor targeted drug delivery because of their unusual properties, such as their distinct optical properties caused by their quantum confinement effects. Because of their intrinsic fluorescence and special qualities that allow them to function as a multifunctional nano system, QDs are also a great option.This includes their capacity to support targeted drug delivery and enhance the bioavailability and stability of medications by extending their in vivo circulation period and enhancing their dispersion

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QD'S MODIFICATION HELPS IN TARGET DRUG DELIVERY

The modification of quantum dot (QD) surfaces plays a crucial role in enabling their function as targeted drug delivery systems. By attaching specific ligands—such by way of antibodies, polyethylene glycol (PEG), peptides, DNA, or small molecules—to the surface, QDs are tailored for selective interaction with receptors on diseased cells or tissues. This facilitates precise delivery of drug molecules to desired biological targets while also allowing QDs to act as fluorescent probes for real-time imaging and tracking of drug distribution in vivo.

The drugs are typically loaded onto QDs through covalent links, electrostatic interactions, or encapsulation within polymeric matrices. Hydrophilic or hydrophobic QDs can be integrated into nanoparticle systems using biodegradable polymers, enabling controlled and extended drug release. Once inside the body, the drug-carrying polymer gradually degrades, releasing the therapeutic cargo at the target site, thereby optimizing treatment efficiency and reducing systemic side effects.

For instance, research has demonstrated the successful loading of the anti-cancer drug Adriamycin onto QDs, where surface modification with hyaluronic acid promoted binding to the CD44 receptor on tumour cells. Such systems have shown enhanced tumour targeting, increased fluorescence for imaging, and improved therapeutic results due to their dual action. Another example is the encapsulation of PEGylated graphene QDs with cancer therapies like gefitinib in polylactic acid (PLA) microspheres, which allow pH-dependent release and sustained drug delivery. These platforms not only ensure efficient targeting but also provide valuable imaging feedback during treatment.

Overall, size and surface chemistry are critical for QD-based drug carriers, influencing circulation time, tissue penetration, and excretion. By flexibly designing their surface and encapsulating drugs within biocompatible materials, quantum dots present a promising avenue for achieving simultaneous targeted therapy and diagnostic imaging in personalized medicine.

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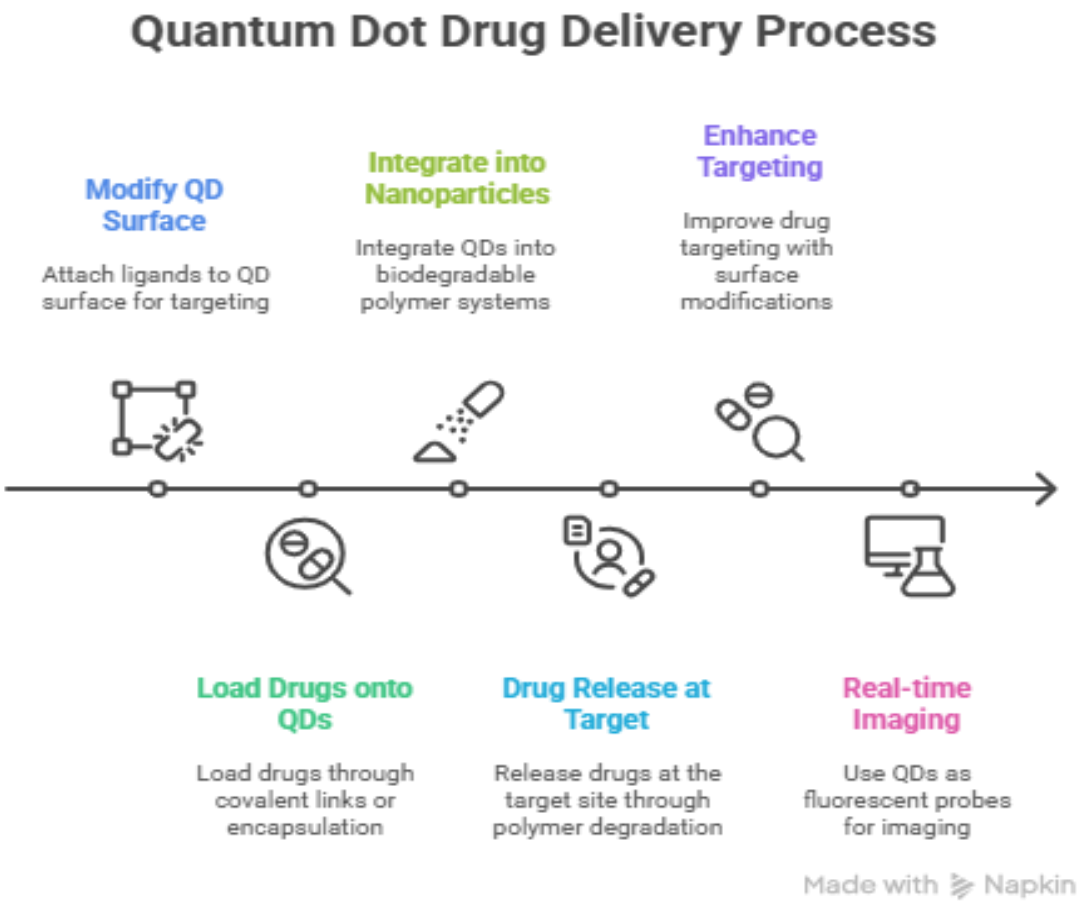

CYTOTOXICITY

The cytotoxicity of quantum dots (QDs) is a significant challenge hindering their broader application in clinical imaging and therapies. This toxicity largely stems from their chemical makeup, as many QDs contain heavy metals such as cadmium and indium. Once internalized by living cells, QDs have the potential to release these ions, especially if their protective shells become unstable or degrade. Environmental factors like pH, temperature, and the physicochemical characteristics of QDs—including their size, concentration, coating, and durability—can influence the degree to which toxic effects manifest.

Studies have shown that QDs can accumulate in various organs, such as the heart, liver, kidneys, spleen, brain, and reproductive organs, with retention sometimes lasting for weeks or months. This accumulation can result in elevated metal ion concentrations in tissues and disrupt normal cellular functions, leading to cardiotoxicity and other organ-specific damage. Additionally, QDs are known to generate reactive oxygen species (ROS) within cells, which causes oxidative stress, damages DNA, and can trigger cell death through apoptosis or autophagy pathways. ROS-related toxicity is considered a major mechanism in QD-induced cellular damage, especially for heavy metal-containing nanocrystals.

Researchers have explored surface modifications, including encapsulation in silica coatings or functionalization with polymers, to reduce ion leakage and acute toxicity. Thicker silica shells, for example, can significantly suppress metal ion release, providing enhanced protection for nearby cells. However, this method leads to an increase in particle size, which may complicate biodistribution and limit applications where smaller nanoparticles are preferred. Though protective coatings can minimize immediate toxic effects, the long-term accumulation and the possibility of chronic toxicity remain important issues and must be addressed through additional research.

Ongoing efforts to design safer QDs focus on alternative, non-toxic materials, and on improving protective strategies through advanced surface engineering—such as robust shell coatings and the use of biocompatible polymers. These upgrades aim to

preserve the unique optical properties of QDs while minimizing any adverse biological effects. Ultimately, thorough evaluation of biocompatibility, repeated safety assessments, and deeper studies of QD behaviour within biological systems are essential before these nanoparticles can be safely used in clinical settings.

FUTURE ASPECTS WITH QUANTUM DOTS

The versatility of QD opens up possibilities for innovative cancer treatment strategies. Black phosphorus material has recently been found to work as a "nano knife" in conjunction with ROS generation, enabling precise tumour ablation, according to the text. The potential uses of BPQDs as nanocarriers and nano knives in the administration of chemotherapy medications are being investigated. The future depends on the use of non-toxic, biocompatible QD materials along with a thorough understanding of the related pharmacokinetics and pharmacodynamics to facilitate their short-term transition from research to clinical applications.

Surface-modified QDs can be used for precise gene delivery. Preclinical and clinical stages have not yet been attained, despite recent reports of investigations on QD gene delivery at the cellular level. Together with chemotherapy and radiation therapy, these technologies could offer a more comprehensive cancer treatment.

When human intelligence advances, potential biomedical advancements may be made, pushing nanotechnology past its current bounds and making quantum dots a crucial component of these advancements.

CONCLUSION

At the intersection of nanotechnology and oncology, quantum dots have become a ground-breaking tool that offers major benefits for targeted therapy, imaging, and cancer detection. Their distinct optical and physicochemical characteristics enable precise tumour targeting, enhanced contrast in imaging, and efficient drug delivery, all of which enhance therapeutic effectiveness and reduce adverse effects. Clinical application is hampered by potential cytotoxicity, long-term accumulation, and the need for improved surface modification. Moving QD-based advancements from lab to bedside will require more study into biocompatible materials, improved surface engineering, and a deeper understanding of pharmacokinetics. Quantum dots have the potential to play a significant role in both scientific advancement and cancer treatment in the future.

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